Characterising the effectiveness of coral restoration to build reef resilience: a socio-ecological perspective

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My father always told me that life is like a journey on a train. You often choose your destination, hop on a car, and go for the ride. Reaching that destination might be fast, or it might be very slow. Sometimes you might need to travel to different "places" before you can reach your final destination. You will also meet other people on the train, who will impact your journey in many different ways. Sometimes, you might even decide to change your plans altogether, so you can follow them. Importantly, you need to be both driven towards your goals and open to new experiences and chance encounters. At some point you will find yourself back at the station. Think carefully about where the next train will take you…
I embarked on the PhD train about four years ago for what has most certainly been one of the most interesting journeys of my life so far. Not only did it take me to many amazing places around the world, but it has also widened my understanding and love of coral reefs. I won't deny that I am very happy to see it come to an end, but I am also proud and grateful for the many people that have helped me along the way.

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I certify that the present thesis

Characterising the effectiveness of coral restoration to build resilience: a socio-ecological perspective

is, to the best of my knowledge and belief, original and my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

Margaux Yvonne Sophie Hein

ABSTRACT

Coral restoration is rapidly becoming a mainstream strategic reef management response to address dramatic declines in coral cover worldwide. Restoration success can be defined as increased resilience of the restored reef areas leading to improved ecosystem services, with multiple socio-cultural and economic benefits. However, there is often a mismatch between the objectives of coral restoration programs and the measures used to assess their effectiveness. In particular, scales of ecological benefits currently assessed are limited in both time and space, and very few studies account for potential socio-cultural and economic benefits. The research presented in this thesis explores the effectiveness of current long-term restoration programs across the socio-ecological spectrum and provides best-practice recommendations on how coral restoration can be used to improve reef resilience.

In **Chapter 2**, I review the literature to identify current measures of coral restoration success. I found that current measures of coral restoration effectiveness are largely limited to evaluating the short-term, biological responses of coral fragments to transplantation. Over 50% of current studies measure coral restoration success solely through two indicators: fragment survival and growth. Additionally, 53% of these studies monitor restoration outcomes for only one year post-transplantation at most; only 5% of studies monitored outcomes for longer than five years.
To address the lack of measures assessing the success of restoration programs against key socio-ecological principles, I developed an integrated scale of coral restoration effectiveness based on ten indicators of reef and social resilience. These were: three ecological indicators linked to the structural integrity of reefs (benthic cover, structural complexity, and coral diversity); three ecological indicators linked to the functional integrity of reefs (coral recruitment, coral health, and fish biomass); and four socio-cultural and economic indicators of social resilience (satisfaction, stewardship, capacity building, and economic benefits). In Chapters 3 to 6, I test the efficacy of these indicators by evaluating the overall socio-ecological effectiveness of four well-established coral restoration programs in Thailand, the Maldives, the Florida Keys, and St Croix in the US Virgin Islands. All four programs have practiced coral restoration for eight to 12 years, but use different coral restoration

methodologies, including a variety of artificial structures (Thailand), transplantation onto steel-frames (the Maldives), and direct transplantation onto the reef substrata (Florida Keys and Virgin Islands). The four programs are located in different reef regions, each with specific socio-economic settings, making them good case studies to evaluate the effectiveness of coral restoration.

In Chapters 3 and 4, I explore the effect of restoration practices on the structural and functional integrity of reefs, both of which are integral to improving ecosystem services. At the four program locations, I compare coral assemblages (**Chapter 3)** and fish communities (**Chapter 4)** at restored sites with those at neighbouring degraded sites and at nearby control reference sites. I found that hard coral cover and structural complexity were consistently greater at restored compared to unrestored (degraded) sites. However, patterns in coral diversity, coral recruitment and coral health among restored, unrestored and reference sites varied across locations, highlighting differences in methodologies among restoration programs. Altogether, differences in program objectives, methodologies and the state of nearby coral communities were key drivers of variability in the responses of coral assemblages to restoration.

It is a common assumption that coral restoration efforts will result in an increase in both the abundance and diversity of reef fishes, thereby improving ecosystem function and restoring some ecosystem services. However, very few studies have specifically looked at the response of the fish assemblage to coral restoration. Results presented in **Chapter 4** demonstrate that the responses of fish assemblages are more complex than expected, with location-, site- and size-specific responses. Overall, I found that fish communities did not show overly strong and/or clear responses to the outcomes of any of the restoration programs.

The results for the six ecological indicators varied across my four study locations, highlighting the varied potential for coral restoration to improve ecological resilience. I found positive results for structural indicators at all four locations, but indicators linked to functional integrity only improved in response to the Thailand program, particularly in response to steel structures and concrete reef balls that held a diversity of corals above the substratum. Comparisons among programs revealed that the limited diversity in the corals used in restoration was an issue for the ecological resilience of restored sites in the Maldives, and high disease susceptibility of monospecific stands of target species of *Acropora* was an issue in both the St Croix and Florida Keys programs. Factors likely to affect fish colonisation of restored sites, such as connectivity to healthy fish populations, timing of colonisation, and complexity and coral diversity at the restored sites, require further consideration.

Understanding local stakeholders' perceptions of restoration success is critical to better integrate their needs in the planning, management and ultimately the long-term sustainability of restoration efforts. In Chapters 5 and 6, I evaluate the socio-cultural and economic indicators of restoration success by evaluating local stakeholders' perceptions of their respective restoration programs. In **Chapter 5**, I use semi-structured interviews to identify the perceived benefits and limitations of coral restoration efforts. Respondents were stratified across groups of people involved first-hand in the restoration efforts and members of the local community. Stakeholders' perceptions of coral restoration effectiveness encompassed far more than just ecological considerations, suggesting that coral restoration can be a powerful tool to enhance agency, hope and stewardship, thereby strengthening coral reef conservation strategies. Respondents also revealed key points likely to improve the outcomes of coral restoration efforts, such as the need to better embrace socio-cultural dimensions in goal setting, evaluate ecological outcomes more broadly, secure long-term funding and improve management and logistics of day-to-day practices.

In **Chapter 6**, I use semi-structured interviews to assess local stakeholders' perceptions of the socio-cultural and economic outcomes of coral restoration across the four socio-cultural indicators developed in Chapter 2. I firstly examine the subjectivity and context dependencies of people's perceptions about program success. Results revealed complex perceptions that varied among locations and groups of respondents. Secondly, I compare their perceptions of ecological outcomes to the ecological results my underwater surveys revealed about the responses of coral and fish assemblages to restoration (Chapters 3 and 4). Altogether, stakeholders generally perceived that the outcomes of coral restoration are highly important across all four socio-cultural and economic indicators of social resilience. In particular, the importance of restoration for two metrics, reef stewardship and user satisfaction, were consistently rated as very high at all four locations, highlighting the strong potential for coral restoration to improve the resilience of local communities. Responses suggest that increased involvement of local communities and improved communications of objectives and results could maximise the successful delivery of socio-cultural and economic outcomes within the respective local communities.

Finally, I integrate the physical and social results from this study to develop best-practice recommendations for the use of coral restoration as a management strategy to improve reef resilience across the socio-ecological spectrum. Recommendations for maximising ecological components of resilience include designing restoration structures to maximise complexity and coral diversity, selecting sites to maximise biological connectivity and site qualities like water quality and depth. Recommendations for improving the socio-cultural benefits of restoration include increasing and sustaining engagement of local communities and key stakeholders, securing long-term funding, and providing strong leadership.

This thesis demonstrates that the potential for coral restoration efforts to improve the socio-ecological resilience of degraded reef systems is high but complex, as potential can vary across restoration programs with different objectives, designs and management strategies. The ten indicators of coral restoration effectiveness synthesised and tested herein are practical tools for improving the long-term monitoring of such efforts. While climate action is needed first and foremost to address dramatic, climate-change driven declines in the world’s coral reefs, results from this thesis demonstrate that coral restoration can be used as a valuable tool to improve the resilience of both coral reefs and the local communities that rely on them.

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CHAPTER 1

General Introduction

1.1 The rise of ecological restoration in the Anthropocene

It is widely accepted that mankind is altering the earth's natural systems at unprecedented rates. In fact, many argue that we have entered a new era called the "Anthropocene" in which humans have become a force capable of altering ecosystems (Carey 2016). Examples of distinct human signatures are found in geological records (i.e., plastics, metal, pesticides traces in sediment cores, see Waters et al. 2016), biological systems (i.e., increased rate of biodiversity extinctions due to habitat loss and overexploitation, see Vitousek et al. 1997), and both atmospheric and oceanic systems (i.e., rapid increases in CO_2 and CH_4 concentrations in the atmosphere, increases in sea-surface temperature (Solomon et al. 2008, Smith et al. 2013)). This new era represents a shift in mankind's relationship with the earth's resources. Consequently now, continued intense exploitation results in the loss rather than gain of goods and services at local and global scales. For example, large scale deforestation of the Amazon rainforest not only diminishes the potential for carbon sequestration, thus contributing to global climate change (Exbrayat et al. 2017), but also increases erosion, de-regulates water and river flows, and promotes spread of infectious diseases (reviewed in Foley et al. 2007). Continued intense resource exploitation since the mid-20th century, has led to widespread calls for active intervention strategies for managing resources.

More than two decades ago, it was realised that "*humanity's dominance of Earth means that we cannot escape responsibility for managing the planet*" (Vitousek et al. 1997). In such a context, ecological restoration, defined as "the process of assisting the recovery of an ecosystem that has been degraded or destroyed" by the Society for Ecological Restoration (SER 2004), is gaining momentum as a conservation strategy (Jordan & Lubick 2011, McDonald et al. 2016). Ecological restoration dates back to the beginnings of agriculture in the form of landscape alterations and the first land management practices (Jordan & Lubick 2011). It is now used globally to ameliorate a variety of ecosystems, particularly to respond to and manage human-driven climate change (Jordan & Lubick 2011, Keenleyside et al. 2012, McDonald et al. 2016). Overarching goals of ecological restoration are anthropocentric in essence, centred around the conservation of biological diversity and the maintenance of ecosystem goods and services while integrating socio-cultural needs and realities (McDonald et al. 2016). Restoration is also a central component of international targets for sustainability and biological conservation, from the Convention of Biological Diversity (Aichi Biodiversity target 14, SCBD2010), to the Bonn Challenge (IUCN 2011), and the United Nations Agenda for Sustainable Development (Goal 15, UN 2016) (McDonald et al. 2016).

1.2 Threats to coral reef ecosystem: How we went from vibrant ecosystems to coral graveyards in the last 30 years

Pressures on coral reef ecosystems are escalating in the Anthropocene. Just in the duration of my PhD candidature, about one-third of the corals on the Australian Great Barrier Reef have died as a result of two back-to-back mass coral bleaching events (Hughes et al. 2017, 2018) and several destructive cyclones (e.g. Nathan 2015, Debbie 2017, (GBRMPA 2017, Gordon et al. 2018)). In other reef regions, Hurricanes Irma and Maria have devastated reefs in the Caribbean and Florida Keys, adding to the intensification of hurricane impacts on reefs in that region (Gardner et al. 2005). Moreover, these destructive events are just the tip of the iceberg of what coral reefs around the world have had to endure in the past 40 years. Coral cover is declining at alarming rates regionally and globally (Gardner 2003, Bruno & Selig 2007, Hughes et al. 2017) due to a variety of stressors such as diseases, bleaching, run-off from coastal development, and predation by corallivore starfish (Bellwood et al. 2004, Fabricius 2005, Harvell et al. 2007, Babcock et al. 2016). The impacts of these stressors are further exacerbated by synergistic relationships among them, e.g., between coral bleaching and disease (Maynard et al. 2015), and between increased ocean acidification and sea-surface temperature warming (Bellwood et al. 2004, Hughes et al. 2018). Coral declines often lead to phase-shifts from coral-dominated reef systems to alternate states characterised by less diversity, structural complexity and functionality. Caribbean reefs are striking examples of this process as they have lost 80 to 90% of their coral cover since the

1980s and are now dominated by macro-algae (Hughes 1994, Gardner et al. 2003, Cote et al. 2005, Bruno et al. 2009).

The loss of associated reef ecosystem goods and services is one of the most concerning consequences of coral reef degradation. Ecosystems goods and services are benefits that humans derive directly and/or indirectly from functioning reef ecosystems (Moberg & Folke 1999, Millenium Ecosystem Assessment (MEA) 2005). In coral reef systems, these benefits include goods that can be extracted from reefs such as fish, seafood, and other raw materials (Moberg & Folke 1999), and services accruing from sustaining critical biological processes, for example protecting coasts from high-wave energy (Ferrario et al. 2014) and supporting social and cultural services (Moberg & Folke 1999, Spalding et al. 2017). These benefits and services are central to the well-being of local communities (Costanza et al. 2014). They also highlight human dependence on reefs, especially in terms of their monetary value.

Valuing reef ecosystem services is difficult because it requires assessing the value of both market and non-market-based services which many argue are simply invaluable (e.g. McCauley 2006). Yet, as a relative measure of an ecosystem's benefits to mankind, valuation is critical, allowing comparisons across ecosystems and aiding agendas for sustainable development (Costanza et al. 2014). As a reference, the value of coral reefs' ecosystem goods and services varies from a conservative US$352,249/ha/year (Costanza et al. 2014) to a high of over US$2 million/ha/year (DeGroot et al. 2012). In 2017, Deloitte et al. also valued the Great Barrier Reef at US$56 billion for its economic, social, and iconic attributes. These enormous sums reflect the importance of coral reef ecosystems to the functioning and well-being of society. They reinforce the need for conservation strategies that halt the loss of coral cover and preserve reef ecosystem functions. Active intervention strategies that are increasingly advocated include those that could promote coral reef resilience (i.e., the capacity of reefs to sustain and/or recover from disturbances (Mumby et al. 2007)) and maintain reef functional processes above thresholds that could lead to phase-shifts away from coral-dominated reef systems (Hughes et al. 2010, Anthony et al. 2017, Darling & Côté 2018).

1.3 Coral restoration: A solution?

In the last five years, coral restoration has gained wider acceptance as an interventionist approach to reef management (Rinkevich 2014, Anthony et al. 2017, Boström-Einarsson et al. 2018). Although it has been actively used and studied for the past 30 years (Alcala et al. 1982, Auberson 1982, Edwards 2010), it has only recently been considered a serious option. Different approaches to coral restoration are currently used in different reef regions. For example, in the Indo-Pacific, a majority of coral restoration efforts occur in response to reef destruction through blast-fishing, as a way to restore the physical integrity of reefs (Fox et al. 2005, Raymundo et al. 2007, Dela Cruz et al. 2014, Fox et al. 2019). In contrast, most restoration efforts occurring in the Caribbean region aim at growing and restoring endangered species of *Acropora* (Johnson et al. 2011, Young et al. 2012).

While there are a variety of physical and biological approaches to coral restoration (Edwards & Gomez 2007), coral transplantation is the one most widely used (Epstein et al. 2003, Rinkevich 2005). Coral transplantation simply refers to planting coral fragments on the reef and usually follows a three-step process: 1. Collection, 2. Rearing, 3. Planting (Figure 1.1). Coral fragments are either sourced from a donor colony, collected as “fragments of opportunity” (i.e., naturally broken off and laying unattached on the reef), or grown from coral larvae following a coral spawning event (Figure 1.1). Typically, fragments are then grown in a coral nursery (*in-* or *ex situ*) until they are large enough to be planted (Rinkevich 1995). Finally, the corals are planted back onto the reef either directly or onto artificial structures (Edwards & Gomez 2007, Figure 1.1).

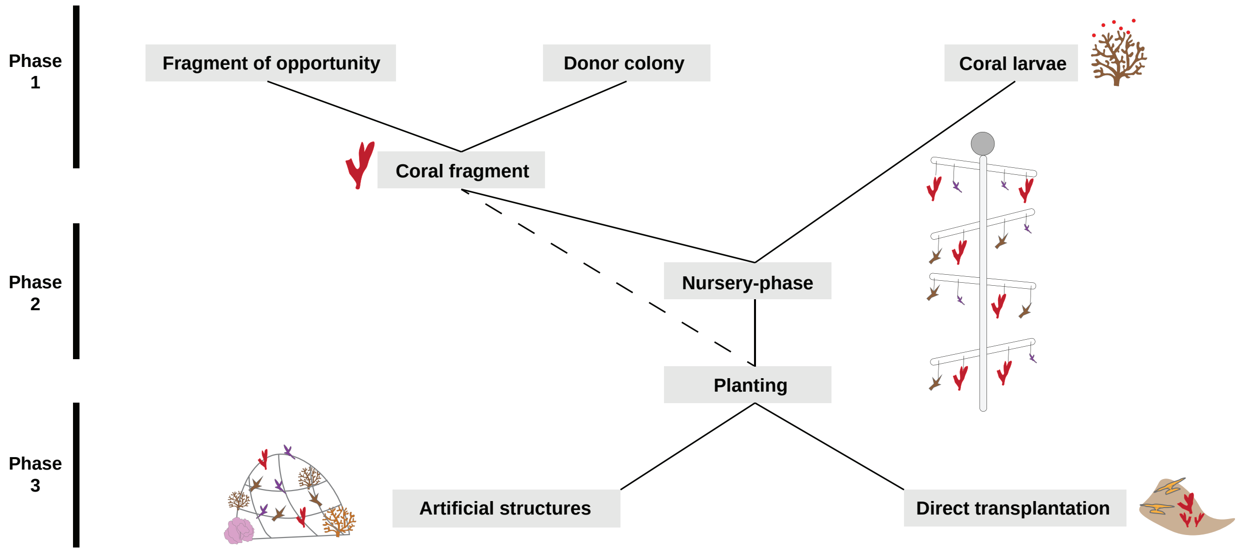


Figure 1.1 Concept diagram for the coral transplantation process

It is important to recognise that coral restoration on its own will not stop global drivers of coral declines such as increasing temperatures and ocean acidification (Yap 2003; Precht et al. 2005; Edwards & Gomez 2007). However, nor will conventional management strategies such as marine protected areas (Bruno et al. 2018) or water quality improvement plans (Brodie et al. 2012). Instead, these tools can be integrated in multidisciplinary adaptive management frameworks, to address scientific uncertainties associated with the biological, physical, and socioeconomic factors at play in coral reef ecosystems (Yap 2000; Hobbs & Harris 2001; Edwards & Gomez 2007; Foley et al. 2010).

Coral restoration is increasingly advocated internationally to further support more traditional, passive reef conservation methods (e.g. marine protected areas). Active reef restoration efforts are now occurring throughout the Caribbean as part of the US National *Acropora* Recovery Plan that aims to grow and restore endangered species of Caribbean *Acropora* (Johnson et al. 2011, Young et al. 2012). On the Great Barrier Reef, coral restoration is an integral part of the new “Reef Blueprint” to better manage the resilience of the marine park in the face of increased anthropogenic and climate-change related disturbances (Great Barrier Reef Marine Park Authority 2017).

1.3.1 Challenges in using coral transplantation for restoration

Planting corals back onto degraded reefs is a direct strategy to rapidly increase coral cover, but many question the efficacy and adequacy of coral restoration to combat coral reef ecosystem collapse (Precht et al. 2005, Hughes et al. 2018). A number of key reasons underpin this.

Firstly, coral restoration is logistically difficult and expensive. It is resource intensive requiring specific training and expertise to operate underwater, and costs vary greatly between developed and developing countries (Bayraktarov et al. 2015). Additionally, the cost of materials and techniques used range from US$10,000/ha to over 2 million US$/ha (Bayraktarov et al. 2015, Chamberland et al. 2017). As such coral reefs are amongst the most expensive ecosystems to restore (Bayraktarov et al. 2015).

Secondly, the scale of potential benefits from coral restoration efforts is also widely criticised. Spatially, many argue that the scale of coral planting is insufficient compared to the scale at which reefs are deteriorating globally (Yap 2000, 2003; Precht et al. 2005; Edwards & Gomez 2007; Omori 2011; Ammar et al. 2013). Corals are slow-growing organisms, and the temporal scales necessary for coral transplants to become established, and reefs to recover (i.e., 2 to 5 years, Pearson 1981, Graham et al. 2015) contrast greatly with the notion of using coral restoration as a "quick-fix" post-degradation (Jaap 2000; Van Diggelen et al. 2001; Sleeman et al. 2005).

Thirdly, coral restoration ecology is a young field of science. While restoration of terrestrial systems has been common practice since the beginning of the 20th century, coral restoration only emerged as a potential reef management strategy about 30 years ago (Young et al. 2012). As a result, coral restoration ecology is still widely regarded as in its infancy, with lots to be learned about improving existing methods (Edwards & Gomez 2007, Normile 2009).

Overall, there is limited scientific evidence of the effectiveness of coral restoration with a paucity of studies assessing coral restoration outcomes (Clark & Edwards

1995; Chapman & Underwood 2000; Hawkins et al. 2002; Rinkevich 2005; Abelson 2006; Bruckner 2006; Wapnick & McCarthy 2006; Guest et al. 2011). In particular, no list of standardised, measurable indicators of coral restoration success is currently available in the literature, hindering the development of guidelines for reef managers (Edwards 2010). Existing measures of coral restoration success are currently focused on two metrics: transplant growth and transplant survival (Okubo et al. 2005; Yap 2009; Guest et al. 2011; Bayraktarov et al. 2015; see Chapter 2 for a further review) and are thus inadequate to measure reef-scale effects of coral restoration efforts, as well as critical functional attributes of reefs including potential effects of coral restoration on fish biomass, coral health, and levels of coral recruitment.

Recent coral restoration approaches are trying to address these limitations of cost and scale. Approaches include: developing techniques to improve performance of coral transplants (e.g. use of mid-water coral nurseries (Rinkevich (2015)), increasing the spatial scale of restoration (e.g. larval enhancement experiments (DelaCruz & Harrison 2017)), maximising genetic diversity of transplants via sexual reproduction tools (Guest et al. 2010), harnessing benefits of other reef processes at the restoration site such as herbivory (Ladd et al. 2018), and a variety of others (e.g. assisted evolution (van Oppen et al. 2015), large-scale seeding of coral juveniles (Chamberland et al. 2017), improving coral fragments' attachment methods (Tagliafico et al. 2018), micro-fragmentation (Page et al. 2018), and low-tech substrate stabilisation (Haisfield et al. 2010)). Yet all such approaches are largely still in development or experimental phases and not yet deployed at scale (reef-wide scales of 100s to 1000s of m^2).

1.3.2 Coral restoration as a tool to improve the socio-ecological resilience of coral reef systems

The potential for coral restoration efforts to improve reef resilience merits particular attention. Objectives of ecological restoration are increasingly moving away from restoring ecosystems towards a historic baseline. Instead current efforts are increasingly focused on engineering ecosystems to ensure the sustainable delivery of ecosystem services in the face of climate change (Perring et al. 2015). In coral reef ecosystems, coral restoration has the potential to improve both extrinsic and intrinsic resilience (Darling & Cote 2018). Intrinsic resilience refers to corals' capacity to withstand disturbances and could be improved by genetically engineering corals to boost adaptation to changing conditions before transplantation (van Oppen et al. 2015, Anthony et al. 2017, Darling & Cote 2018). Extrinsic resilience refers to characteristics at the scale of the reef ecosystem and could be improved by maximising refuges from climate change at micro-scales (e.g. increased structural complexity; Hoogenboom et al. 2017), and macro-scales (e.g. facilitating connectivity amongst healthy ecosystems; Hock et al. 2017, Darling & Cote 2018).

Beyond biological and ecological processes, the resilience of reefs as socio-ecological systems also needs to be addressed, where the social component of reef resilience refers to the resilience of nearby communities and reef ecosystem services that humans derive directly and/or indirectly from functioning reef ecosystems. Coral restoration is, in essence, a social endeavour, as people are involved in all stages of the restoration process, from design to planting and monitoring. The human dimension is increasingly recognised as a central component of ecosystem management enabling better understanding of the socio-cultural, economic, and institutional forces driving changes (Folke 2006). Solving the coral reef crisis necessitates recognition that human activities are at the centre of the problem, and thus need to be part of the solution as well (Hughes et al. 2010). The potential for secured delivery of ecosystem services from restoration efforts also has a very anthropocentric focus (Martin et al. 2017). And finally, coral restoration could be a tool to potentially restore agency around the management and governance of reef resources (Bennet et al. 2017).

1.3.3 The sustainability of coral restoration efforts

Characterising coral restoration effectiveness requires a framework in which social and ecological outcomes are robust and long-lasting, and thus aligned with socio-ecological principles of sustainability. In Valentin & Spangenberg's (2000) framework, sustainability is characterised by an equilibrium across four inter-connected dimensions: ecological (nature conservation), socio-cultural (ethical), governance (political), and economic (prosperity and health). In such a framework, the sustainability of coral restoration efforts would rely on four main components:

1. Satisfactory ecological outcomes, 2. Adequate project governance from project management to legislative support, 3. Economic benefits, and 4. Socio-cultural benefits through increased opportunities for education and stewardship of local reef resources.

1.4 Thesis objectives

My aim in this thesis is to characterise coral restoration effectiveness in the context of socio-ecological resilience and sustainability of reef systems. Specifically, I had the following objectives:

A. Evaluate and measure existing indicators of coral restoration success (Chapter 2)

For the first part of this study, I performed a comprehensive review of the literature on coral restoration ecology in order to i) examine the existing objectives of coral restoration, ii) assess the current approaches to evaluating coral restoration effectiveness. The review also enabled me to identify and develop a set of measurable indicators of coral restoration effectiveness for reef resilience that encompassed both sociological and ecological dimensions, which I use in subsequent chapters. The socio-ecological indicators developed provide a comprehensive set of measurable attributes that can be used in integrated management frameworks and provide ground for adaptive capacity.

B. Characterise coral restoration effectiveness using socio-ecological indicators at four well-established coral restoration programs (Chapters 3 to 6)

To test the indicators developed in Chapter 2, I visited four coral restoration programs located in Thailand, the Maldives, the Florida Keys, and the US Virgin Islands (Figure 1.2). These four programs were chosen because they are well-established having been actively involved in coral restoration activities for eight to ten years, they use a variety of restoration techniques, and occur in different regions of the world providing a global perspective. Each program has different restoration objectives in very specific socio-economic contexts, as well as different local environmental histories and disturbances at the sites. I use these four programs to characterise coral reef restoration success using the socio-ecological indicators developed in Chapter 2. To explore the ecological structural and functional integrity of the restored reef areas, I looked at the effect of coral restoration on the coral assemblages (Chapter 3), as well as on the fish assemblages (Chapter 4). To evaluate the socio-cultural and economic outcomes of the coral restoration programs, I used semi-structured interviews with local key stakeholders at each location. The interviews assessed their perceptions of the socio-ecological benefits and limitations associated with restoration (Chapter 5), as well as the socio-cultural and economic outcomes of the coral restoration efforts (Chapter 6).

C. Develop best-practice guidelines for the use of coral restoration as a reef management strategy (Chapter 7)

Finally, I used the results from Chapters 2 to 6 to discuss best-practice guidelines to maximise the use of coral restoration as a tool to sustain and improve coral reef resilience. These guidelines were based on the four restoration programs investigated in this project and align with the four dimensions of sustainability: ecological, socio-cultural, governance, and economic dimensions.

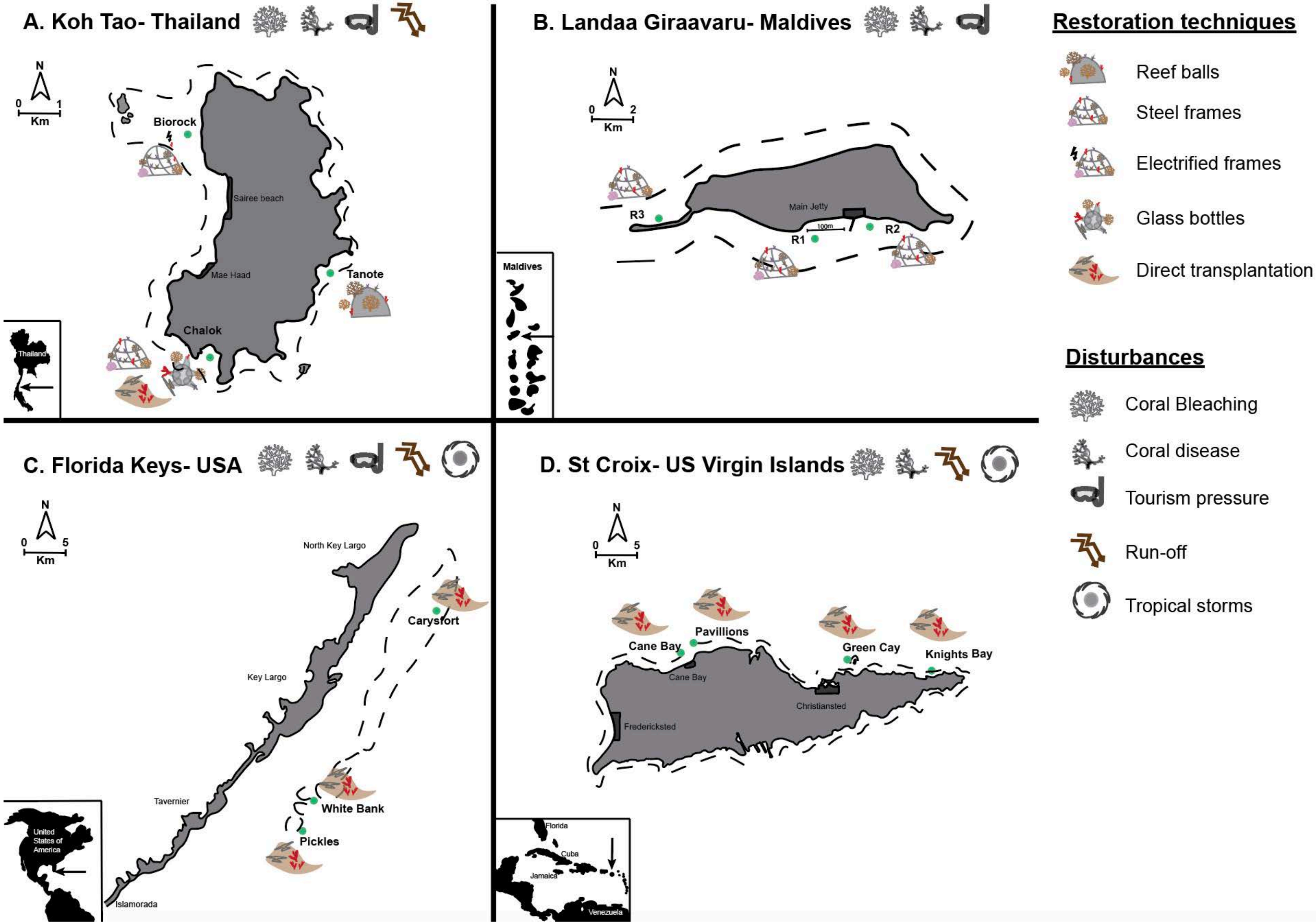


Figure 1.2 Map of the four coral restoration programs used as case studies in this study, with details on the restoration techniques used, as well as the history of disturbances at each location

CHAPTER 2

Literature review: The need for broader ecological and socio-economic tools to evaluate the effectiveness of coral restoration programs

Hein MY, Willis BL, Beeden R, Birtles A (2017) The need for broader ecological and socio-economic tools to evaluate the effectiveness of coral restoration programs. Restoration Ecology 25(6):877-883

2.1 Introduction

Coral restoration is gaining increasing attention as a tool to supplement current management strategies for coral reef conservation, largely because of accelerating declines in coral populations globally (Gardner et al. 2003; Pandolfi et al. 2003; Hoegh-Guldberg et al. 2007; De'Ath et al. 2012). The increasing frequency of disturbances, coupled with limitations associated with traditional conservation strategies (e.g. marine protected areas; Mora & Sale 2011, Santo 2013), has led to a growing number of managers and coral reef scientists calling for the introduction of more active measures (e.g., Bellwood et al. 2004; Sale et al. 2014; Millenium Ecosystem Assessment 2005; Rinkevich 2008; van Oppen et al. 2015). Coral transplantation, the act of moving and securing coral fragments on reef substrata (Edwards & Gomez 2007), is the most widely used coral restoration strategy (Epstein et al. 2003; Rinkevich 2005), and transplantation-based restoration projects have burgeoned around the world over the last 30 years (Rinkevich 2014). Most coral transplantation projects follow the coral gardening concept (Rinkevich 1995), for example growing coral fragments on mid-water floating nurseries until they reach a suitable transplant size. Although use of a nursery phase has improved the initial survival of coral transplants (Rinkevich 2014), mismatches remain between the scale at which coral reef restoration techniques are applied, the spatial scale required for coral reef recovery and the extent of current knowledge about the effectiveness of restoration programs.

Coral restoration science has been the subject of much skepticism within the scientific community (Precht et al. 2005). Many argue that coral reef ecosystems are too complex and not well-enough understood for coral transplantation initiatives to be effective (Precht et al. 2005). In particular, the spatial scale of potential benefits arising from transplantation programs has been criticised as inadequate to address the scale at which reefs are deteriorating (Yap 2000, 2003; Omori 2011; Precht et al. 2005; Edwards & Gomez 2007; Ammar et al. 2013). Moreover, temporal scales required to establish benefits from coral transplantation programs contrast with the notion of using reef restoration as a “quick-fix” response to degradation (Jaap 2000; Van Diggelen et al. 2001; Sleeman et al. 2005). On the other hand, such mismatches of spatial and temporal scales do not rule out the use of coral transplantation within frameworks of adaptive management actions that operate across a wide range of scales. Finally, it is widely acknowledged that replanting corals will not stop global drivers of coral loss, such as climate change or ocean acidification, highlighting that coral transplantation on its own is not an effective management strategy (Yap 2003; Precht et al. 2005; Edwards & Gomez 2007). Nevertheless, integration of coral transplantation within long-term, multi-disciplinary adaptive management frameworks has merit as a strategy to address scientific uncertainties associated with the biological, physical, and socio-economic factors at play in coral reef ecosystems (Yap 2000; Hobbs & Harris 2001; Edwards & Gomez 2007; Foley et al. 2010).

The lack of scientific assessment of the outcomes of coral reef restoration projects has also been widely criticised (Clark & Edwards 1995; Chapman & Underwood 2000; Hawkins et al. 2002; Rinkevich 2005; Abelson 2006; Bruckner 2006; Wapnick & McCarthy 2006; Guest et al. 2011). Effectiveness or “success” in coral restoration has traditionally been linked to only two indicators: transplant growth and transplant survival (Okubo et al. 2005; Yap 2009; Guest et al. 2011; Bayraktarov et al. 2015) and currently, no suite of standardised measurable attributes is available for evaluating the effectiveness of ecological restoration of coral communities. This lack of specific criteria impedes evaluation and comparison of coral transplantation effectiveness, and ultimately hinders the development of clear guidelines outlining what does and does not work in restoration programs (Edwards 2010). Adequate characterisation of the effectiveness of restoration programs requires a set of clearly defined indicators linked to specific objectives and the underlying reef-wide properties they are measuring, as well as appropriate monitoring timeframes

(Chapman & Underwood 2000; Hobbs & Harris 2001; Wapnick & McCarthy 2006; Breed et al. 2016). In this chapter, I review the current state of coral restoration science, with a particular focus on evaluating indicators currently used to characterise the effectiveness of restoration programs, and develop a broader set of holistic indicators that reflect restoration effectiveness across ecological and socio-economic dimensions. While the review has a strong focus on experimental coral transplantation studies due to the limited number of reports on broader-scale restoration initiatives in the peer-reviewed literature, the indicators proposed are applicable to assessments of both restoration experiments and broader-scale restoration efforts.

2.2 Current status of coral restoration science

A standardised search of the peer-reviewed literature was performed to compile published studies on coral restoration and transplantation. Transplantation is the most widely used coral restoration technique (Epstein et al. 2003; Rinkevich 2005) and use of this term ensured that the papers reviewed focused on applied studies of both restoration ecology (i.e., the science of restoration that underpins ecological restoration) and ecological restoration, rather than on passing references to restoration concepts. The search was standardised using the query "Coral* AND Restoration AND Transplantation" in the online tool within the "Web of Science" database. The query returned 102 results but was narrowed down to 83 applied studies that used transplantation for coral restoration (Table S2.1, Appendix S2.2). For each paper, I recorded the objective of the experiment, the indicator(s) of success used, and the length of time of the monitoring program. Of the 83 studies reviewed, the majority (50 studies) are experimental with a narrow research focus, highlighting the more limited representation of broader-scale coral restoration efforts in the peer-reviewed literature.

2.2.1 Objectives of coral restoration

Six primary objectives for coral restoration were deduced from the 83 studies reviewed (Table 2.1). Interestingly, while climate change-associated disturbances may not have been an initial focus of early coral restoration efforts, I found that

objectives were generally aligned with underlying management principles designed to promote reef resilience in a changing climate. Resilience refers to the capacity of an ecosystem to sustain repeated disturbances while securing key functional and structural attributes (Holling 1973; Hughes et al. 2010; McClanahan et al. 2012). Actions that maximise the two key resilience components, recovery and resistance, are the focus of resilience-based management, an approach that seeks to use resilience indicators as foresight to guide management decisions (West & Salm 2003; Nyström et al. 2008; McClanahan et al. 2012; Anthony et al. 2015).
Recovery was an important focus of the studies reviewed, as reflected in objectives one and two listed in Table 2.1: “Accelerate reef recovery post-disturbance” and “Re-establish a self-sustaining and functioning ecosystem”. The importance of resistance (i.e., the capacity of the ecosystem to cope with a disturbance like coral bleaching or storms) was also recognised, as reflected in objectives three and four: “Mitigate anticipated coral loss prior to a known disturbance” and “Reduce population declines and ecosystem degradation” (Table 2.1). Mitigation actions referred to in both these objectives aim to maintain or even enhance biodiversity, thereby providing communities with added resistance to disturbances. Objectives five and six, “Provide alternative, sustainable livelihood opportunities” and “Promote coral reef conservation stewardship”, respectively (Table 2.1), address broader, socio-cultural and economic aspects of reef resilience, consistent with mounting recognition that educating and empowering local communities is crucial to address the “governance crisis” associated with global coral reef declines (Hughes et al. 2010). The inclusion of social considerations in coral restoration objectives is critical. Social factors are inherent to the concept of resilience from a socio-ecological perspective, with anthropogenic forces recognised as essential drivers of ecological system identity (Cumming et al. 2005; Folke 2006).

Table 2.1 Review of six primary objectives deduced from 83 studies using coral transplantation for reef restoration (See Table S2.1 for further details of each of the 83 studies reviewed)

#	Objective	Rationale	Studies
1	Accelerate reef recovery post-disturbance	Natural reef recovery is a lengthy process ranging from 5 years to decades (e.g. Pearson 1981, Connell et al. 1997), and transplanting coral colonies on reefs affected by recruitment	Maragos 1974; Clark & Edwards 1995; Jaap 2000; Raymundo 2001; Epstein et al. 2003; Rinkevich 2005; Garrison & Ward

		limitation may kick-start the recovery process	2008; Ferse 2010; Van Oppen et al. 2015
2	Re-establish a self-sustaining, functioning reef ecosystem	Objective here is not to restore a known coral community but rather rehabilitate coral reef ecosystem processes to secure critical ecosystem services	Alcala et al. 1982; Auberson 1982; Thornton et al. 2000; Miller & Barimo 2001; Epstein et al. 2003; Abelson 2006; Edwards & Gomez 2007; Edwards 2010; Omori 2011; Rinkevich 2014; Hunt & Sharp 2014
3	Mitigate anticipated coral loss prior to a known disturbance	Mitigation strategy, whereby coral colonies are relocated from a soon-to-be impacted site to a safer site	Harriot & Fisk 1988; Thornton et al. 2000; Salvat et al. 2002; Edwards & Gomez 2007; Kilbane et al. 2008; Seguin et al. 2008
4	Reduce population declines and ecosystem degradation	Conserve endangered coral species, and safeguard critical ecosystem services on threatened coral reefs by increasing coral cover, diversity, and overall structural complexity. This objective also includes creating artificial "sacrificial sites to move tourism pressures away from pristine, natural reef areas."	Edwards & Clark 1998; Thornton et al. 2000; Forrester et al. 2012; Kirkbride-Smith et al. 2013; Van Oppen et al. 2015
5	Provide alternative sustainable livelihood opportunities	Coral transplantation efforts may provide alternative livelihood opportunities, such as enhancing fisheries habitat, tourism, and coral farming	Heeger & Sotto 2000; Spurgeon 2001; Edwards 2010; Young et al. 2012
6	Promote coral reef conservation stewardship	Involvement in coral transplantation will foster conservation stewardship through increased education and research opportunities	Fisk & Job 2008; Edwards 2010

Closer inspection of results presented in the 83 studies revealed that the majority (60%) did not directly address the stated objectives, but instead their objectives would more accurately be represented as testing the biological responses of coral fragments to transplantation (Figure 2.1a). Such studies represent experimental approaches to coral restoration ecology, but lack a broader coral restoration goal *per se*. Where broader objectives were given (33 studies), only the first four objectives were represented (i.e., accelerate reef recovery post-disturbance; re-establish a self-sustaining, functioning ecosystem; mitigate anticipated coral loss prior to a known disturbance; and reduce population declines and ecosystem degradation) (Figure 2.1a). Re-establishment of a self-sustaining, functioning ecosystem was the primary objective for 48% of these studies (Figure 2.1b). Socio-economic outcomes were never listed as a primary objective of these studies, and socially-driven objectives were included as a secondary objective in only three cases (Heeger & Sotto 2000; Job et al. 2006; De La Cruz et al. 2014).

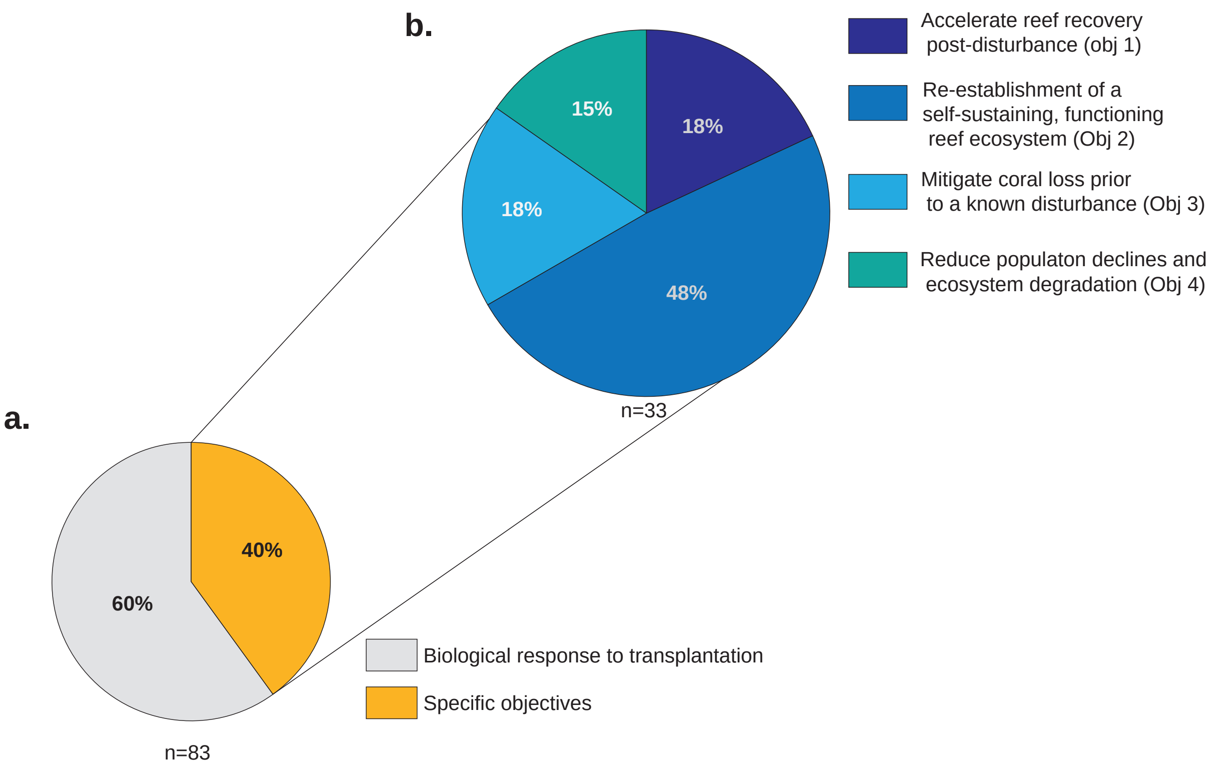


Figure 2.1 Comparison of objectives for peer-reviewed, restoration studies (n=83): a) proportions of studies listing specific biological versus broad resilience-related objectives for coral transplantation studies; and b) proportions of studies listing one of four resilience-related objectives. Search based on Web of Science, using the keywords “Coral* AND Restoration AND Transplantation” (Table S2.1)

The nearly two-fold greater number of studies focusing on the biological response of fragments post-transplantation than on any of the other objectives identified suggests that, to date, a major goal of coral restoration studies has been to work through the technicalities of transplantation during the "initial establishment phase" (Le et al. 2012). While a thorough understanding of technicalities associated with coral transplantation is critical to the success of such projects (e.g. Boch & Morse 2012), the ubiquity of this focus confirms a mismatch between the scales at which studies have evaluated the success of restoration ecology experiments and the scales needed to evaluate the effectiveness of ecological restoration from a resilience and sustainability perspective (Edwards & Gomez 2007).

2.2.2 Indicators of coral restoration effectiveness

Transplant growth and transplant survival were the two most widely used indicators of the effectiveness of restoration programs, with 88% of studies (n=83) using either one or both indicators, sometimes in combination with other indicators (Figure 2.2). The majority of studies (55%) focussed solely on these indicators, and among these studies, using both growth and survival as indicators of success was the most common strategy. One-third of studies (33%) used a greater range of indicators, combining transplant survival and/or growth with other indicators of success (Figure 2.2). Only 12% of studies looked at indicators of success other than transplant growth and/or survival, for example: fish and invertebrate communities associated with transplants, enhanced local recruitment, fusion of transplants to the substrate, reproduction of transplants, fragment health, or changes in local coral cover (Figure 2.2).

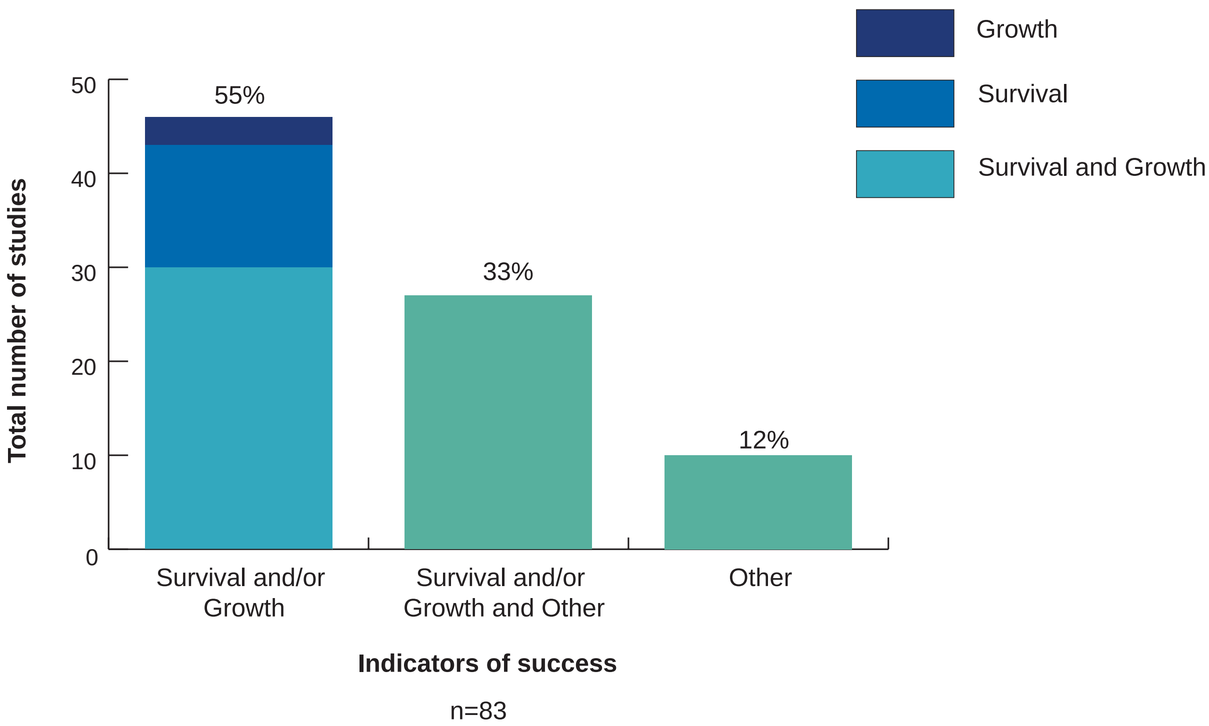


Figure 2.2 Indicators of coral restoration success used in peer-reviewed studies of coral transplantation and restoration (n=83). Percentages above each histogram relate to the total number of studies. Search based on Web of Science, using the keywords “Coral* AND Restoration AND Transplantation” (Table S2.1)

The dominance of transplant growth and survival, both measures of the biological response of coral fragments to transplantation, as criteria for coral restoration success reflects the technical focus of most studies reviewed. While these two criteria are inherent to the notion of transplantation success, they are focused on success at the scale of the fragment. Many other factors, like coral and macro-algae cover, or structural complexity, are equally important for the establishment of a functional coral reef community (Maynard et al. 2015; Graham et al. 2015), and thus for characterising success at a broader reef scale. Also noteworthy is that criteria for measuring growth are typically not standardised across studies. Accordingly, transplant growth has been quantified as the number of new branches (e.g. Bowden-Kerby 1997; Chilcoat 2004), rate of linear extension (e.g. Custodio & Yap 1997; Romatski 2014) or as changes in the buoyant weight of fragments (e.g. Yap & Molina 2003). Lack of a standardised approach and differences in growth strategies among species, limit the capacity to compare outcomes of transplantation programs among studies.

Broader indicators of success that have implications for ecosystem restoration and relate more directly to resilience considerations are parameters like herbivore biomass and diversity, and rates of natural recruitment. Unfortunately, use of such measures was limited to a small number of studies (n=8 studies for fish and invertebrates, and n=6 studies for rates of natural coral recruitment) (Table S2.1). Only three studies (Job et al. 2006; Miller et al. 2016; Montoya-Maya et al. 2016) measured coral cover as an indicator of coral restoration success. The criterion "coral health" was sometimes listed (n=11 studies), but the coral health indicators recorded (e.g. condition of the coral fragment, signs of bleaching, competition with algae, injury, signs of disease, invertebrate colonisation of fragments) tended to be qualitative rather than quantitative. Overall, measures of coral health were typically absent from the coral transplantation studies reviewed.

Many studies advocated the need to consider social, economic, and cultural factors in the evaluation of restoration initiatives (e.g. Yap 2000; Van Diggelen et al. 2001; Epstein et al. 2003; Bruckner 2006; Hernandez-Delgado et al. 2014). Yet, criteria that assess the socio-cultural and economic dimensions of coral transplantation projects were virtually absent from the studies reviewed. Such considerations are central to the continuous and sustainable delivery of ecosystem services and thus are inherently linked to the long-term success of a restoration project (Schrack et al. 2012). For example, cultural ecosystem services, such as aesthetic, recreational, and educational opportunities can be direct outcomes of coral transplantation programs and are readily linked to a variety of measures associated with wellbeing, from security and basic materials for life, to health and enhanced social relationships and social cohesion (Millenium Ecosystem Assessment 2005). Coral transplantation activities may thus increase the value of reef ecosystem services, not only through nature conservation and social outcomes, but also directly through a range of economic enterprises, such as increased alternative livelihood opportunities and resource security for industries dependent on reefs (Lirman & Shopmeyer 2016).

Another gap in the current characterisation of coral restoration effectiveness is the lack of economic considerations. Coral reefs are amongst the most expensive ecosystems to restore, with costs ranging from 11,717 USD/ha to 2,879,773 USD/ha (Bayraktarov et al. 2015). Costing coral restoration efforts is difficult as the different phases of restoration need to be accounted for, from the collection of coral fragments, to the transplantation, maintenance, and monitoring of transplants (Spurgeon 2001; Edwards 2010). Costs also vary tremendously depending on the source of coral transplants (e.g. fragments of opportunity versus sexually-reared larvae) (Garrison & Ward 2008; Guest et al. 2014; Okubo & Onuma 2015). Moreover, while coral reef ecosystems are widely recognised as one of the highest valued ecosystems on the planet (>USD 350,000 ha-1 yr-1) (De Groot et al. 2013; Costanza et al. 2014; Deloitte Access Economics 2017), the few studies that have attempted to value the benefits of coral restoration (Spurgeon 2001; De Groot et al. 2013) have found that costs still outweigh the benefits. Better understanding of the economic value of the benefits of restoration efforts is critical to develop more cost-effective solutions (Okuba & Onuma 2015).

In summary, indicators of success currently being used in coral restoration science focus on a comprehensive understanding of the biological responses of corals to transplantation. These considerations are critical to maximise initial transplantation success, but insufficient to characterise the effectiveness of coral restoration in terms of reef resilience and provision of ecosystem services in socio-ecological dimensions. More indicators related to long term success at a broader ecological scale, like reproductive output of transplanted fragments or structural complexity of ensuing coral assemblages, as well as indicators related to socio-economic success, like increased stewardship or reef user satisfaction (Okuba & Onuma 2015), should be included in the characterisation of coral restoration effectiveness, especially for experimental studies looking into coral restoration success.

2.2.3 Monitoring for coral restoration effectiveness

The mean duration of monitoring for all coral transplantation studies was less than two years (22.5 ± 2.4 months); however, the majority (53%) of studies were monitored for one year or less. Only 5% of studies were monitored for more than five years (Figure 2.3), and the duration of monitoring was not specified in 2% of studies. Although such timeframes are reasonable for evaluating the feasibility of transplantation techniques, they are not appropriate for evaluating their usefulness for re-establishing coral communities. In two of the long-term studies, coral growth and survival were initially low but eventually mirrored trends observed for *in situ* coral colonies (Garrison & Ward 2012; Forrester et al. 2014). In another study, fish assemblages increased over time as the restored areas became colonised by a range of other organisms and increased in complexity (Yeemin et al. 2006). All long-term studies also stressed important year to year variations in the growth and survival of transplanted coral fragments due to disturbances like storms or bleaching events. Overall, the typically short-term nature of monitoring programs limits the understanding of coral restoration effectiveness.

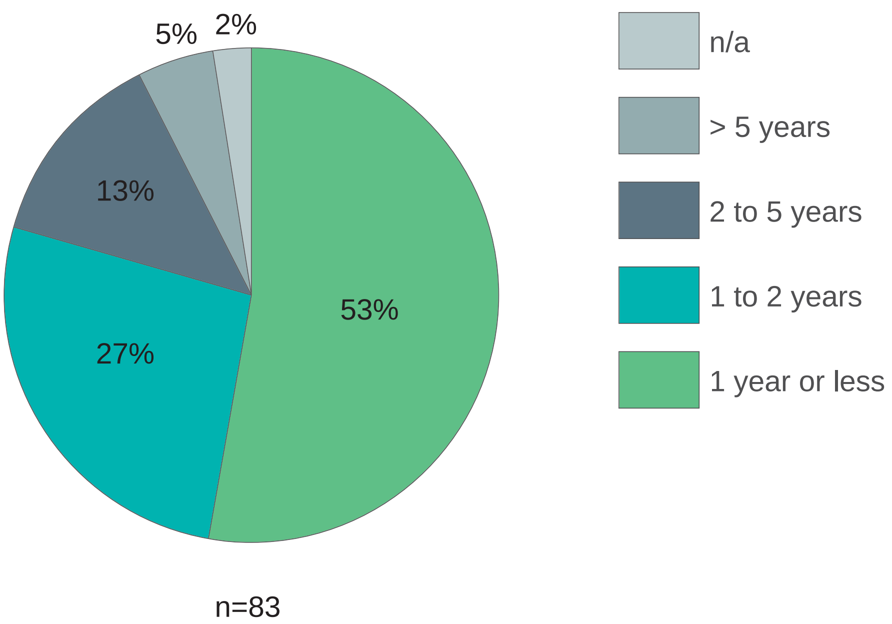


Figure 2.3 Duration of monitoring programs described in peer-reviewed restoration studies (n=83). Search based on Web of Science, using the keywords “Coral* AND Restoration AND Transplantation” (Table S2.1). n/a refers to “not available”

Monitoring ecological restoration success typically involves a two-stage monitoring program corresponding to: (a) an initial establishment phase following transplantation related to the biological response of transplants (e.g. initial growth post transplantation, fusion of fragment to substrata), and (b) a long-term building phase when transplants are growing in size and have potentially broader environmental and socio-economic benefits (Kanowski & Catterall 2007, Le et al. 2012). Attributes monitored may change throughout the course of these phases, with long-term ecological and socio-economic benefits becoming more apparent in the second phase. The duration of each phase is likely to vary among projects. For example, the length of the initial establishment phase will depend on factors such as

initial reef state, transplantation method(s) used, morphology of corals used, initial fragment size etc.; the length of the long-term building phase will depend on the initial goals of the study, the attributes monitored, as well as funding availability.
In general, survival and growth of transplants after one year are ineffectual indicators of restoration effectiveness in either experimental studies or restoration programs, given many of the life-history characteristics of scleractinian corals (e.g. slow growth, natural fragmentation, reproductive output related to colony size) and the stochastic nature of environmental disturbances, like storm events and warm thermal anomalies causing bleaching (Yap 2003). Also, some studies have suggested that coral fragments undergo a “transplant stress” period, during which growth may be reduced (Lirman et al. 2010; Forrester et al. 2012, 2014), and therefore surveying biological responses over insufficient timeframes may provide misleading results (Yap 2003). The complexity of coral reef ecosystems means that natural reef recovery can be a lengthy process ranging from five years to decades (e.g. Pearson 1981; Connell et al. 1997; Gilmour et al. 2013; Graham et al. 2015). Correspondingly, evaluations of the effectiveness of coral restoration programs may not provide meaningful data relating to sustainability and resilience objectives unless monitoring is continued for five or more years. The nature and focus of such evaluations will thus vary according to funding cycles and whether the goal of the study is to explore ecological aspects of coral restoration or to initiate a broader-scale restoration program. Future funding applications should include monitoring as an inherent part of their objectives.

2.3 Proposed socio-ecological indicators of coral restoration effectiveness

My analyses revealed a mismatch between commonly-stated objectives for coral restoration programs and attributes currently used to assess coral restoration effectiveness because of an understandably strong focus on short-term biological responses of coral fragments to transplantation. While many advocate the need for systematic long-term monitoring programs (e.g. Chapman & Underwood 2000; Yap 2003; Wapnick & McCarthy 2006; Edwards 2010; Breed et al. 2016), standardised protocols with a set of measurable, timely indicators relating to specific objectives are currently lacking. In order to incorporate reef resilience and the sustained provision of ecosystem services into the scope of measures of reef restoration effectiveness, I propose a suite of ten ecological, socio-cultural and economic indicators for inclusion in effective monitoring programs. These indicators fit within a framework of positive interactions that link people and communities with coral restoration and reef resilience, as outlined below (see also Figure 2.4). It is important to note that not all of the ten indicators proposed may be relevant for all attempts to characterise coral restoration effectiveness. For example, while some of the socio-cultural and economic indicators are critical to assess the sustainability and adaptive capacity of applied coral restoration efforts, they may be beyond the scope of coral restoration ecology studies that have a narrower research focus. Choice of indicators will thus vary between experimental studies and broader coral restoration efforts. I also recommend selecting indicators of success with careful consideration of reference sites, which largely determine the relevance of effectiveness assessments, as discussed further below. Finally, the temporal and spatial scope of each of the ten indicators require particular attention, as their relevance and suitability will vary with the context and goals of the study.

2.3.1 Ecological indicators of coral restoration effectiveness

Terrestrial restoration programs have a long history of evaluating their effectiveness and provide important insights into the types of ecological indicators that best measure the resilience of an ecosystem (Society for Ecological Restoration 2004; Ruiz-Jaen & Aide 2005). Following a review of ecological indicators of terrestrial restoration success, Ruiz-Jaen & Aide (2005) suggested that comprehensive evaluations require a minimum of two indicators in each of the following three categories: diversity, vegetation structure, and ecological processes. More recently, eleven indicators of coral reef resilience have been developed to identify resilient reefs for targeted management actions, based on empirical scientific evidence, feasibility of monitoring, and their perceived importance, as identified by expert reviewers (McClanahan et al. 2012).

I combined these two concepts to identify indicators that reflect both restoration success and reef resilience, and propose that the following six ecological indicators capture the effectiveness of coral restoration: (1) coral diversity, (2) herbivore biomass and diversity, (3) benthic cover, (4) recruitment, (5) coral health, and (6) structural complexity (Table 2.2, Figure 2.4; see Appendix S2.1 for further descriptions of these indicators). While other indicators can be used to measure the ecological success of coral restoration projects, I argue that these six indicators are comprehensive and accord with both ecological restoration and reef resilience guidelines (Ruiz-Jaen & Aide 2005; McClanahan et al. 2012).

Table 2.2 Six ecological indicators of restoration effectiveness. The column "Category" lists corresponding indicators advocated by Ruiz-Jaen & Aide (2005). Restoration objectives are as described in Table 2.1. Monitoring phase refers to restoration stages described in Le et al. (2012)

Indicator	Category	Link to coral restoration objective	Monitoring phase
1.Coral diversity	Diversity	Objectives 1,2,4,5,6	1. Initial establishment phase 2. Long-term building phase
2.Herbivore biomass and diversity	Diversity	Objectives 1,2,4,5,6	1. Initial establishment phase 2. Long-term building phase
3.Benthic cover	Substrate structure	Objectives 1,2,3,4,5,6	1. Initial establishment phase 2. Long-term building phase
4.Recruitment	Substrate structure	Objectives 1,2,4	2. Long-term building phase

5.Coral health	Ecological processes	Objectives 1,2,3,4	1. Initial establishment phase 2. Long-term building phase
6.Structural complexity	Ecological processes	Objectives 1,2,4	1. Initial establishment phase 2. Long-term building phase

A paramount consideration for evaluating the ecological success of coral restoration is that variables measured at restored sites should be compared with those at control and reference sites (Wortley et al. 2013). Control sites should be nearby degraded but unrestored reefs to distinguish between the effects of intervention versus natural recovery (i.e., no treatment effect). Reference sites should be nearby non-degraded reefs that provide a baseline reference for restoration goals (i.e., the desired end community) (Society for Ecological Restoration 2004) and for the selection of appropriate indicators. Use of both control and reference sites will provide insights that deepen understanding of ecological succession processes in coral restoration. Survey techniques used may vary depending on the time, material and human resources available, as well as on the accuracy and precision targeted by the program (Leujak & Ormond 2007).

2.3.2 Socio-cultural and economic indicators of coral restoration effectiveness

Socio-cultural and economic considerations are essential components of coral restoration effectiveness because of their potential to increase sustainable livelihood opportunities (Objective 5; Table 2.1) and build capacity in local communities (Objective 6; Table 2.1). Successful outcomes associated with both of these components are important for enhancing the long-term sustainability of restoration efforts. Sustainability is typically organised around four key elements that are interconnected to form a theoretical “prism of sustainability” (a.k.a pillars of sustainability): Socio-cultural (ethical), Environmental (nature conservation), Governance (political), and Economic (prosperity and health) (Valentin & Spangenberg 2000; Spangenberg 2004). In such a framework, restoration initiatives will only be successful if the costs, both monetary and to society, are outweighed by the benefits (again both monetary and to society) (Bayraktarov et al. 2015). Recognising the socio-economic and governance dynamics of the region and stakeholders involved in the coral restoration program is thus crucial (Ammar 2009). Not only is coral restoration effectiveness ultimately linked to community support and involvement (Ammar 2009; Schrack et al. 2012; Hernandez-Delgado et al. 2014), but positive feedback to the community from restoration efforts might also be additional indicators of success (De La Cruz et al. 2014).

I took into account considerations of both sustainability and social resilience to propose a list of four socio-cultural and economic indicators of coral restoration effectiveness (Table 2.3, Figure 2.4): (1) reef user satisfaction, (2) stewardship, (3) capacity building, and (4) economic value, and outline rationales for their use in Appendix S2.1. While other criteria may be used, I argue that these four indicators encompass three of the four pillars of sustainability (socio-cultural, economics, and governance), and the fourth pillar (environmental) is adequately covered by the ecological indicators described above.

Table 2.3 List of four socio-cultural and economic indicators of restoration effectiveness. The column “Category” refers to the four pillars of sustainability (Valentin & Spangenberg 2000). Restoration objectives are as described in Table 2.1. Monitoring phase refers stages described in Le et al. (2012)

Indicator	Category	Link to coral restoration objective	Monitoring phase
1.Reef user satisfaction	Socio-cultural Economic	Objectives 2,5,6	1. Initial establishment phase 2. Long-term building phase
2.Stewardship	Socio-cultural	Objectives 2,6	1. Initial establishment phase

			2. Long-term building phase
3.Capacity-building	Socio-cultural Governance	Objectives 2,5,6	2. Long-term building phase
4.Economic value	Economic Governance Socio-cultural	Objectives 2,5,6	1. Initial establishment phase 2. Long-term building phase

Measuring socio-cultural and economic indicators is unexplored territory in coral restoration ecology but methods such as semi-structured interviews have been used effectively to assess terrestrial restoration programs (e.g., Nielsen-Pincus & Moseley 2013, Brancalion et al. 2014). Interviews may target local stakeholders (Key Informant Surveys) (e.g. (Samonte-Tan et al. 2007) and/or members of local communities (e.g. Nielsen-Pincus & Moseley 2013; Brancalion et al. 2014). An important consideration is that the questions asked should focus on both potential benefits and failures so that answers can be used for adaptive management purposes. Ideally, control surveys should also be conducted among neighbouring communities that are not involved in a coral restoration program. Repeated interviews over time would also help to identify developing issues among stakeholders and allow adaptive management to address such issues.

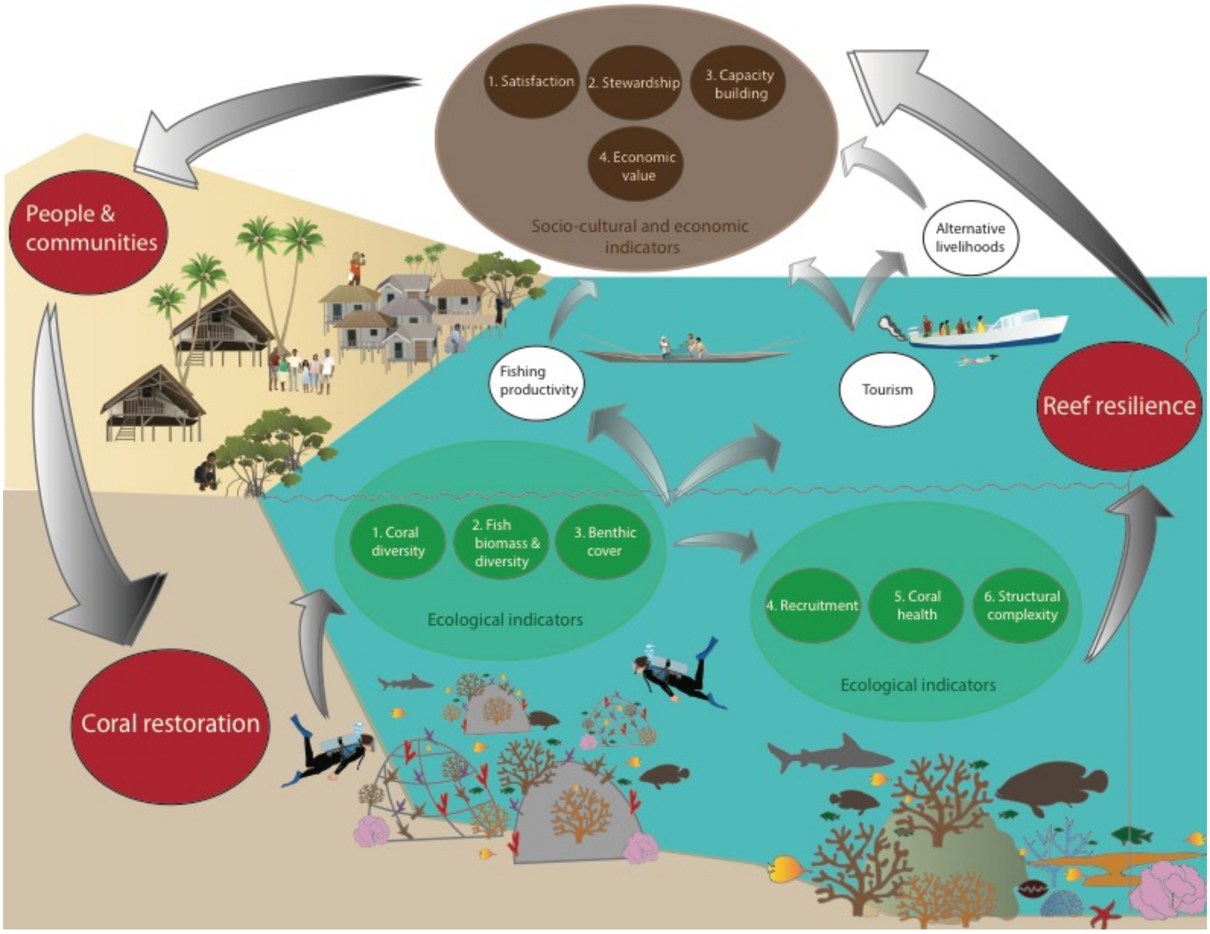


Figure 2.4 Illustration of the framework of positive interactions that link people and communities, coral restoration, and reef resilience. The six proposed ecological indicators are highlighted by green ovals; the four proposed socio-cultural and economic indicators are highlighted by brown ovals

2.4 Building reef resilience through coral restoration

In general, objectives for coral restoration align with all key principles of reef resilience, and there is scope to believe that coral restoration efforts could play an important role in preventing and reversing phase-shifts to undesirable ecosystems, for example by enhancing rates of recovery as disturbances become more frequent, enhancing adaptation (e.g. selective breeding; van Oppen et al. 2015), and by maintaining structural complexity following disturbance events to support communities of coral-associated species. While this review focused on coral transplantation as a restoration strategy, it is important to acknowledge that other coral restoration methods, such as building artificial reefs to create alternative dive sites (Shani et al. 2012) or to reconstruct the physical integrity of a reef area (Jaap 2000), also aim to rebuild or enhance reef resilience. Restoration actions that are focused on reducing damage to reef ecosystems are likely to have similar ecological, socio-cultural and economic benefits as those discussed for coral transplantation in this review.

2.5 Conclusions

This review reveals that, to date, the science of coral restoration has focused primarily on evaluating short-term biological responses of coral fragments to transplantation, wherein coral transplant growth and survival are the most commonly assessed variables, and the mean duration of monitoring is just under two years. While deepening the understanding of coral transplantation techniques and feasibility is a crucial first step, it is insufficient to fully evaluate coral restoration effectiveness in a socio-ecological context. I propose a suite of ten ecological, socio-cultural and economic indicators to comprehensively assess the effectiveness of coral restoration projects in social-ecological dimensions. Indicators were selected following assessment of best-available knowledge of factors characterising coral reef resilience, but further studies are needed to better evaluate the scope of each indicator to represent coral restoration effectiveness on both spatial and temporal scales. Given the accelerating rate at which coral restoration is being applied to reefs worldwide, understanding the successes and failures of such enterprises across all ten indicators is critical. Accounting for a variety of temporal and spatial scales and socio-ecological contexts will optimise coral transplantation efforts so they best contribute to human wellbeing and complement broader adaptive management strategies. Studies using the ten criteria are encouraged to establish a strong foundation from which to investigate the efficacy of coral restoration and elucidate how coral restoration can be used as a proactive management tool to sustain the socio-economic and ecological values of coral reefs and promote reef resilience in the face of a changing climate.

CHAPTER 3

Characterising the effectiveness of coral restoration programs: comparing the response of coral assemblages to restoration in four reef regions

3.1 Introduction

Worldwide declines in coral cover in recent years (Gardner et al. 2003, De'ath et al. 2012, Jackson et al. 2014, Hughes et al. 2017, 2018) are causing reef managers to consider more active, interventionist strategies for reef conservation (e.g., Rinkevich 2008, van Oppen et al. 2015, Anthony et al. 2017). As a consequence, the numbers of coral restoration programs are now burgeoning in most reef regions, including in the Caribbean (Young et al. 2012), Red Sea (Horoszowki-Fridman et al. 2015), South-East Asia region (Shaish et al. 2010), and the South-China Sea (Chou et al. 2009). Common objectives of these programs are to assist the recovery of reefs, protect endangered coral species, promote sustainable alternative livelihoods, and enhance conservation stewardship (reviewed in Chapter 2, section 2.2), but there is a general mismatch between the stated objectives of these programs and indicators used to assess their effectiveness. In general, most assessments of coral restoration effectiveness are based on short-term outcomes largely focused on coral growth and survival post-transplantation (see Chapter 2, section 2.3). This lack of long-term, comprehensive assessments of coral restoration effectiveness is widely criticised (Clark & Edwards 1995, Rinkevich 2005, Guest et al. 2011) and hinders the uptake of coral restoration approaches for use within multi-scale adaptive management frameworks. In addition, many studies are focused on site- or region-specific restoration programs (Young et al. 2012, Schopmeyer et al. 2017), which has made comparative studies difficult and limited the development of broad best-practice recommendations.

The capacity of a coral restoration program to improve the resilience of a degraded reef is considered the gold standard for evaluating its effectiveness. Not only has "managing for reef resilience" become a major focus of reef management (Maynard et al. 2017), but "re-establishing a self-sustaining, functioning coral reef ecosystem after a disturbance" is also the most commonly started objective for coral restoration (see Chapter 2, section 2.2). However, measuring the resilience of a reef community requires accounting for two important aspects of resilience: i) the community's capacity for recovery after a disturbance, and ii) the resistance of the system to disturbance (Hodgson et al. 2015). A community's capacity to recover reflects the extent to which processes and mechanisms, such as reproduction, recruitment and connectivity, present in the degraded system are able to return it to an equilibrium state. Documenting the presence of such processes and mechanisms is critical to evaluating whether a restoration program has achieved the common objective stated above, as well as objectives like "Accelerate reef recovery post-disturbance" (see Chapter 2, section 2.2). Resistance refers to a system's capacity to deal with outside disturbances, such as thermal stress or reduction in water quality without deviating from the equilibrium state. Structurally complex and diverse reefs are typically more resistant to such disturbances (Nyström et al. 2000, West & Salm 2003, Hoogenboom et al. 2017). Documenting these attributes can help to evaluate the extent to which a program is likely to accomplish other common coral restoration objectives, for example "Mitigate anticipated coral loss prior to a known disturbance" and "Reduce population declines and ecosystem degradation" see (Chapter 2, section 2.2).

Reef attributes like hard coral cover, species diversity, and structural complexity are directly related to reef resilience (McClanahan et al. 2012, Maynard et al. 2017) and may be enhanced by restoration programs. Percent hard coral cover is the most widely used metric to document reef recovery (e.g. Osborne et al. 2011), although its use in isolation has limited value (Hughes et al. 2010, McClanahan et al. 2012). At restoration sites, increased hard coral cover may prevent phase-shifts to algal-dominated systems (Hughes et al. 2010), enhance recruitment of juvenile corals to the damaged area (Rogers et al. 1984), as well as regenerate the structural complexity of a degraded reef. Structural complexity may also be increased directly by artificial structures used as surfaces for coral transplants. High structural complexity of reef systems has been shown to decrease the sensitivity of local coral assemblages to extreme weather events (Hoogenboom et al. 2017), and also improve reef recovery post-bleaching (Graham et al. 2015). Increased coral diversity on restored reefs leads to increased biodiversity of associated vertebrates and invertebrates, and hence increased functional diversity present within the reef community. Increased functional diversity increases the resistance of the reef community by expanding the range of its potential responses to disturbances. Assessing the potential for reef restoration to improve reef resilience thus necessitates looking at processes occurring at the scale of the benthic community rather than solely at the scale of coral fragments transplanted to a degraded reef.

In Chapter 2, I identified a set of six ecological indicators that could be used to characterise the resilience of a reef community, based on an evaluation of indicators used in terrestrial restoration (e.g. Ruiz-Jaen & Aide 2005) and reef resilience studies (e.g. McClanahan et al. 2012). These are: (1) coral diversity; (2) herbivore biomass and diversity; (3) benthic cover; (4) recruitment; (5) coral health; and (6) structural complexity (Chapter 2, Table 2.2; see Appendix S1 for further descriptions of these indicators). Although subsets of these indicators have been used to characterise the resilience of reef communities (McClanahan et al. 2012, Maynard et al. 2017), to date, the collective set of indicators has not been applied to assessing the outcomes of a coral restoration program. While the capacity of a coral restoration program to affect one or more of these indicators positively is likely to be constrained by factors such as the degradation state of the reef area to be restored or the types of strategies used to restore the coral community, in combination, they provide a holistic assessment of restoration effectiveness.

The objectives and methodologies of coral restoration programs typically differ among reef regions. Many programs depend on the capacity of corals to reproduce asexually and use either fragments from donor colonies or fragments of opportunity. Following the “gardening concept” developed by Rinkevich (1995), coral fragments are often grown in either *in situ* or *ex situ* nurseries until they reach a suitable size for transplantation. They are then transplanted back onto the reef, either directly onto the reef substrata, or onto purpose-built structures, such as biorocks, cement blocks, or steel frames (Edwards 2010, Young et al. 2012). Alternatively, coral larvae may be reared specifically for restoration projects (Guest et al. 2014). While each methodology has its strengths and limitations in differing contexts, there is a critical need to further our understanding of how these different methodologies impact the resilience of restored reef areas in the long-term to better inform reef managers.

In this chapter, my objective is to evaluate the response of coral assemblages to coral restoration efforts at four well-established coral restoration programs that differ in objectives, methodologies, and socio-cultural settings. At each of the four reef locations, I quantify or characterise five indicators of reef resilience: coral cover, structural complexity, coral diversity, coral recruitment, and coral health. I then compare these five indicators of restoration effectiveness among the four restoration programs to gain insights into how different restoration designs influence the response of coral assemblages to coral restoration. A sixth indicator, fish biomass and diversity is addressed in Chapter 4.

3.2 Materials and Methods

3.2.1 Study sites

Data for assessing five ecological indicators of the resilience of restored coral assemblages were collected at four well-established restoration programs that had been in operation for eight to 12 years to enable assessments of long-term effectiveness of differing restoration approaches. The four programs selected represented four reef regions: 1) New Heaven Reef Conservation Program (NHRCP) on the island of Koh Tao, Thailand; 2) Reefscapers program on the island of Landaa Giraavaru, Maldives; 3) Coral Restoration Foundation in Key Largo, Florida Keys, USA; and 4) The Nature Conservancy on the island of St Croix, US Virgin Islands (Figure 3.1). Each location has a unique history of reef-associated disturbances, therefore objectives for coral restoration varied from growing and restoring endangered species of corals (Florida Keys and St Croix), to restoring coral abundance and diversity on sites that have been degraded by tourism pressure and bleaching events (Koh Tao, and Landaa Giraavaru). Programs also differed in the set of coral restoration techniques used, as outlined below (summarised in Figure 3.1 and Figure 3.2), which provided an opportunity to qualitatively compare the relative effectiveness of different methodologies across the five indicators of reef resilience.

Koh Tao, Thailand

Koh Tao is a moderately-sized, high island (21km^2 in area) located in the Gulf of Thailand. The island has undergone rapid development in the past 30 years and is now considered a global hotspot for SCUBA diving, with over 500,000 visitors every year (Wongthong & Harvey, 2014). This rapid development has been largely unregulated, and resorts, bars and restaurants have replaced primary forests. What were once some of Thailand's most biodiverse and pristine reefs are now under stress from terrestrial run-off and sedimentation (Larpnun et al., 2011, Weterings, 2011; Szuster & Dietrich, 2014), over-use by the local water-based tourism industry (Weterings, 2011; Nichols, 2013), and both land-based and marine pollution (Romeo 2014). Several studies have documented high prevalence of coral disease and other indicators of compromised health (Lamb et al. 2014, Hein et al. 2014, Scott et al. 2017). Mass bleaching events recorded in 1998, 2010, and 2014 have also caused substantial coral mortality (Hoeksema et al. 2013, Phongsuwan et al., 2013).

The restoration program led by the *New Heaven Reef Conservation Program* (NHRCP) was initiated in 2007 to assist the recovery of locally degraded reefs by re-building the complexity of coral assemblages, increasing coral cover, and alleviating diving pressures through widespread education. NHRCP uses a wide range of coral restoration techniques, from direct transplantation of coral fragments into natural holes and crevices on the reef to the building of artificial reef structures. Artificial structures are used preferentially in areas where the reef structure has been compromised by boat groundings, anchors, or smothered by sediment run-off from land. Types of structures used include steel frames, electrified artificial reefs, concrete reef balls, and glass-bottles embedded concrete (Figure 3.2A)

Coral fragments are collected as fragments of opportunity, attached to mid-water ropes and table nurseries (Figure 3.2A) for a few months, and then attached onto the reef or onto one of the artificial structures. Attachment methods vary from epoxy cement to nylon thread, cable ties or fine metal wire, depending on the type of structure. Restored areas are scattered around the island, and most include transplants attached to a variety of artificial reef structures, as well as directly onto the reef (Figure 3.1).

Landaa Giraavaru, Maldives

Landaa Giraavaru is a small sand cay (0.18km^2 in area) situated in Baa Atoll, a UNESCO Biosphere Reserve since 2011, on the western front of the Maldivian atoll chain. One five-star luxury resort, comprised of 23 individual villas, was built in 2004 and occupies the whole cay. Construction of the resort caused substantial structural damage to local reefs, which also suffered mass coral bleaching episodes and widespread coral mortality in 1998 and 2010 (McClanahan et al. 2000, Edwards et al. 2001, Jaleel 2013).

The coral restoration efforts led by the *Reefscapers* group primarily aims to increase biodiversity, reef complexity, and habitat diversity on the “house reef” surrounding the island. They use sand-coated stainless-steel structures, referred to as “coral frames”, as artificial substrata on which to attach coral fragments. Three sizes of frames are used (small, medium, and large), ranging from 110x40cm to 200x110 cm (width x height) (Figure 3.2B). Coral fragments are securely attached to frames with cable ties on land and the frames are then placed on the reef at depths ranging from five to ten metres around the island. As of March 2016, the reef around Landaa Giraavaru hosted 2,800 frames, which covered an area of about 5,500m2 and harboured 40 different species of corals (Figure 3.1). The first frames were populated with corals that were salvaged from the construction site when the resort was built in 2004. Nowadays, coral fragments are collected from colonies living on older frames, specifically targeting colonies that resisted earlier bleaching events.

Florida Keys, USA

The Florida Keys in the United States of America have a long history of disturbances that have resulted in dramatic loss of coral cover and diversity, particularly in the past 20 years (Gardner et al. 2003, Donahue et al. 2008, Ruzicka et al. 2013). Disturbances have included tropical storms (2005, 2008, 2012), coral bleaching associated with both cold-water anomalies (2010) and warm water anomalies (2014), and severe outbreaks of coral disease and of corallivores (Lirman et al. 2011, Williams & Miller 2012, Ruzicka et al. 2013, Miller et al. 2014b). Like Koh Tao, the Florida Keys are a hotspot for reef-based tourism (Johns et al. 2001), and local reefs are thus suffering from a wide range of anthropogenic disturbances, including degraded water quality due to land-based sources of pollution (Kruczinski &

McManus 1999), and high intensities of boating and diving activities (Donahue et al. 2008).

The Coral Restoration Foundation (CRF) was created in 2007 with the specific objective of growing and restoring threatened species of corals in the genus *Acropora* (*A. cervicornis*, and *A. palmata*). Abundances of these two species of corals have declined up to 90% throughout the Caribbean and both have been listed as “critically endangered” by the IUCN since 2008 (Johnson et al. 2011). The Foundation harvests coral fragments from remnant colonies surviving on the reef and places them in coral tree nurseries suspended in the water column at approximately eight metres depth (Figure 3.2C). Once fragments are large enough, they are planted directly onto the reef substrata using a 2-part marine epoxy cement (Figure 3.2C). Restoration efforts extend over 31 sites on 10 reefs along the upper Florida Keys reef tract (Johnson et al. 2011) (Figure 3.1).

St Croix, US Virgin Islands

St Croix is a comparatively large high island (218km^2 in area) forming part of the US Virgin Islands in the Caribbean. Reefs around St Croix have suffered extensively from climate change-related disturbances, similar to those described above for the Florida Keys. Tropical storms in 1989 and 1995 caused extensive reef damage, and several coral disease outbreaks over the past 20 years have caused further coral mortality (Bythell et al. 2000, Fisco 2008). In comparison to the Florida Keys, however, reefs around St Croix are not suffering from intense tourism pressure. *The Nature Conservancy* (TNC) commenced coral restoration efforts in 2009, with the goal of growing and re-stocking endangered species of *Acropora* on local reefs (Shrack et al. 2012). Initially, coral fragments were collected as fragments of opportunity that had been broken from parent colonies naturally by storm or surge events. Currently, fragments are collected from donor colonies and grown in coral tree nurseries, following methods developed by CRF in Florida. Once fragments are large-enough, they are planted back onto the reef using a 2-part marine epoxy cement. Restoration sites are scattered around the island, with a particular focus on *A. cervicornis* restoration on the North Shore reefs of Cane Bay, and on *A. palmata* restoration near Green Cay and Knights Bay (Figure 3.1 and Figure 3.2D).

In summary, coral restoration programs at the two Caribbean sites (Florida Keys and St Croix) focus on transplanting nursery-grown fragments of *Acropora* directly onto reef substrata using two-part marine epoxy, whereas restoration programs in Thailand and the Maldives involve attaching coral fragments onto artificial structures. In Thailand, artificial structures vary among sites (Figure 3.1). In the Maldives, a single type of artificial structure is used, i.e., stainless steel frames (Figure 3.1). In both reef regions (Caribbean vs the Indo-Pacific), reefs associated with one program are located adjacent to a high or continental island (St Croix vs Koh Tao), whereas reefs associated with the other program are adjacent to sand cays (Florida Keys vs Landaa Giraavaru). All four programs had been established for eight to ten years at the time of the surveys.

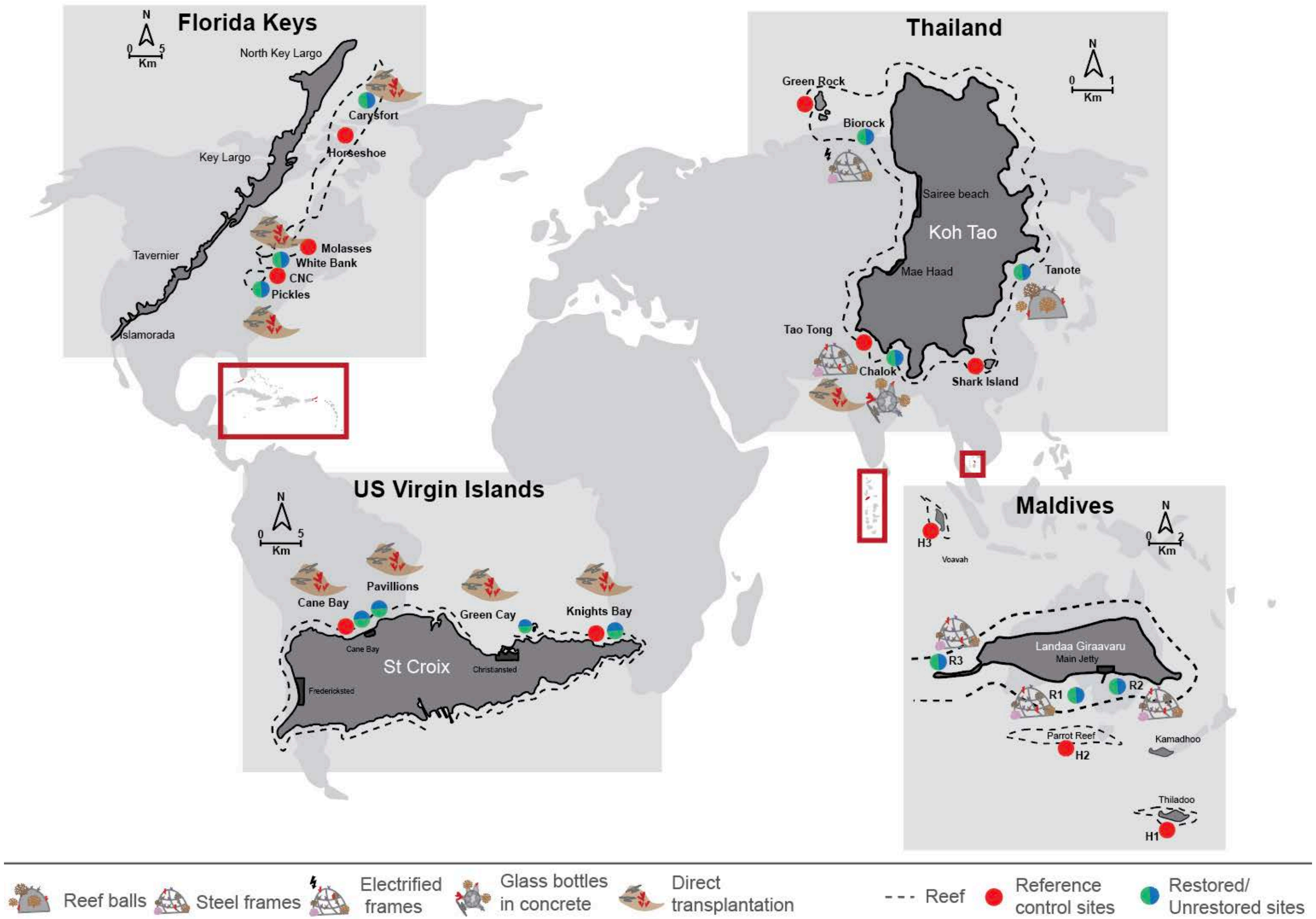


Figure 3.1 Map showing the locations of the four coral restoration programs surveyed and an overview of the restoration strategies used in each program (see key at bottom of figure to interpret diagrams that represent techniques present at each site). Half green and half blue circles indicate adjacent restored and unrestored sites; red circles indicate reference control sites

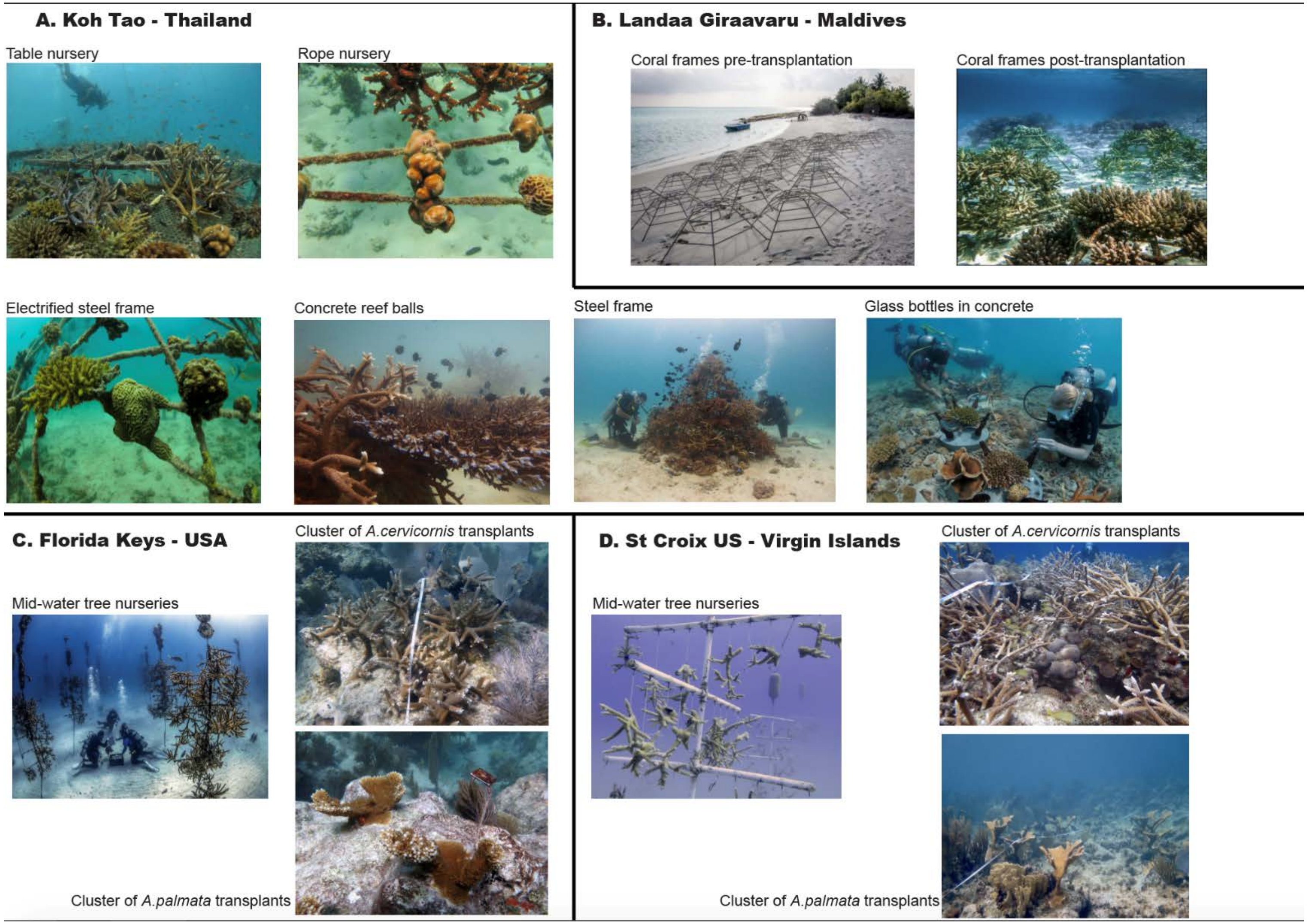


Figure 3.2 Photo montage illustrating coral restoration strategies at the four coral restoration programs surveyed. Photo credits to Margaux Hein, New Heaven Reef Conservation Program, Reefscapers and Marine Savers, and The Coral Restoration Foundation

3.2.2 Measuring ecological indicators of resilience

At each of the four locations, benthic data were compared among replicate restored sites (R), unrestored control sites (UR), and control reference sites (CR). At restored sites, coral fragments had been transplanted either directly onto the substrata or onto artificial structures. Unrestored control sites were degraded sites directly adjacent to restored sites but were not the subject of coral restoration efforts. Control reference sites were comparatively undisturbed sites nearby that were exposed to similar environmental conditions, thus their reef communities were hypothesised to be similar to those at the R and UR sites prior to degradation. A minimum of three replicate sites were surveyed for each of the three treatments (R, UR, CR) at each location, except at St Croix, where the extent of appropriate undisturbed reef area was so small that I could only survey two control reference sites. Thus, three restored sites, three unrestored sites, and three healthy reference sites were surveyed at all locations (except for the two CR sites at St Croix). In addition, a fourth restored site and a fourth unrestored site were surveyed in St Croix.

Benthic data were recorded along three 20m transect lines at each of the three sites per treatment in Koh Tao, Landaa Giraavaru, and the Florida Keys, for a total of 180m surveyed per treatment at each of these locations. In St Croix, the restored area was too small for three replicate 20m transects, thus two replicate 22.5m transects were surveyed at each of four R and four UR sites (i.e., 180m surveyed per treatment) to match the overall areas surveyed at other locations.

Benthic cover and structural complexity

Benthic cover was measured using the line-intercept method, whereby the length of each substrate category falling directly under the line was recorded to the nearest cm. Substrate categories included all corals, which were identified to the genus level, macro-algae, as well as other substrata like sand, rubble, and rocks. Percent cover of each substrate category was then calculated relative to the total length of each transect.

Structural complexity of the reef under each transect was also scored qualitatively using a scale from 0 to 5, where 0= no relief, and 5= high structural complexity and high coral cover, following methods described in Polunin & Roberts (1993) and Graham et al. (2015).

Coral health, generic richness and juvenile recruitment

In addition to line-intercept surveys of coral cover, 2m-wide belts were surveyed along each transect line (i.e., a 40m^2 area per transect), within which all corals were identified to genus and assigned to a coral health category. The number of coral genera recorded in each belt-transect was used as a measure of generic richness. Corals were scored as either healthy or having signs of one or more of seven disease types, and/or a range of compromised health states, such as algal overgrowth, sediment smothering, physical damage or signs of predation. I calculated the prevalence of each disease or compromised health category by calculating its percentage relative to the total number of coral colonies surveyed in each 40m^2 belt transect. Coral health categories and assessment protocols followed guidelines developed by Beeden et al. (2008) for the Indo-Pacific, and Weil & Hooten (2008) for the Caribbean reefs. These survey techniques have been applied previously to assess coral health (e.g. Hein et al. 2014, Lamb et al. 2017). The number of coral juveniles (colonies with a diameter under 5cm; Babcock et al. 2003) was also recorded within each belt transect, and used as a proxy for the number of coral recruits in recent years (Hoey et al. 2011).

3.2.3 Data analysis

All data were analysed using the statistics program R (version 3.4.1, RStudio Team 2015). Analyses described below were applied to metrics measured at each of the four locations separately. Given large geographic distances among the four locations and inherent differences in biodiversity and coral cover among their reef communities, only qualitative comparisons of summative results are made among the four reef locations.

Benthic cover

For each of the four locations, mean percent cover of each substrate category was compared among treatments (R, UR, and CR) and sites (n=3 or 4 sites per treatment type) using multi-factor General Linear models. Treatments were analysed as fixed factors and sites as random factors. A variety of models were tested, including ones where explanatory variables were treated as having either additive or multiplicative effects, and where data were log-transformed. AICc model selection was used to select the model explaining the greatest variation in the data, i.e., the model having the lowest AICc score. Assumptions for model validity were checked through QQ plots and residual plots. When tests failed to meet the assumptions of a Gaussian distribution after log-transformation, non-parametric Kruskal-Wallis tests were applied. When applicable, post-hoc Tukey's HSD tests were also applied to tease out differences among treatments and sites.

Structural complexity

Analyses of mean structural complexity scores among treatments and sites at each location were performed using multi-factor General Linear models, as described above for benthic cover analyses.

Coral generic richness and recruitment

Multi-factor General Linear models were also used to compare generic richness and recruit abundance among treatments and sites at each location. Details of analyses and checks of assumptions were as described above for benthic cover data, except that data were modelled as having "Poisson" or "negative binomial" distributions, as these are most appropriate distributions for count data. Analysis of coral juvenile abundance could only be done for two out of the four sites: Koh Tao and Landaa Giraavaru, as sites in the Florida Keys and St Croix were data deficient for this indicator.

Coral health

Analyses of the percent of corals in each health category among treatments and sites were performed similarly as the analysis described above for benthic cover. Prevalence values for each of four health categories were compared among treatments and sites at each location, namely the prevalence of: healthy corals, diseased corals, corals with other signs of compromised health, and corals with signs of predation.

Coral assemblages

Multivariate analyses were used to assess potential differences in the composition of coral assemblages among treatments, at each location. Prior to analysis, all data were transformed using Wisconsin's double transformation for the fourth root. I then created distance matrices based on "Bray-Curtis" dissimilarity indices, as these are good at detecting ecological gradients (Faith et al. 1987), and applied non-metric Multidimensional Scaling (nMDS) to the transformed dataset. The validity of the nMDS was checked through evaluation of the R^2 value of the linear and non-linear fit, as well as the stress value, which was assumed to be good when <0.2 (Clarke 1993). Coral health and benthic cover data were overlaid on top of the nMDS and ADONIS tests (multivariate ANOVA based on dissimilarities) were used to calculate the contribution of each variable to the spread of the benthic community data, as well as difference in coral assemblages among treatments and sites (pairwise ADONIS). Finally, SIMPER analyses were performed to reveal the cumulative contributions of the most influential coral genera and benthic category to the spread of the data at each location.

3.3 Results

3.3.1 Hard coral cover

Mean hard coral cover was more than twice as great at restored sites compared to degraded, unrestored sites at three out of the four locations: Koh Tao (LM, F=9.5 p<0.001, Table S3.1, Appendix S3), Landaa Giraavaru (LM, F=6.9, p<0.001, Table S3.1), and the Florida Keys (GLM, Residual Deviance=9.4, p=0.005,Table S3.1) (Figure 3.3). In St Croix, there was a trend towards higher hard coral cover at restored sites compared to unrestored sites, but the difference was not statistically significant (GLM, RD=1.7, p=0.375, Table S3.1, Figure 3.3).

In terms of absolute values, mean hard coral cover was higher at restored sites than at control reference sites at the two Indo-Pacific locations (Koh Tao and Landaa Giraavaru); conversely, it was highest at control reference sites at both Caribbean locations (Florida and St Croix; Figure 3.3). However, at all four locations, differences in mean hard coral cover between restored sites and control reference sites were not statistically significant (Figure 3.3, Table S3.1).

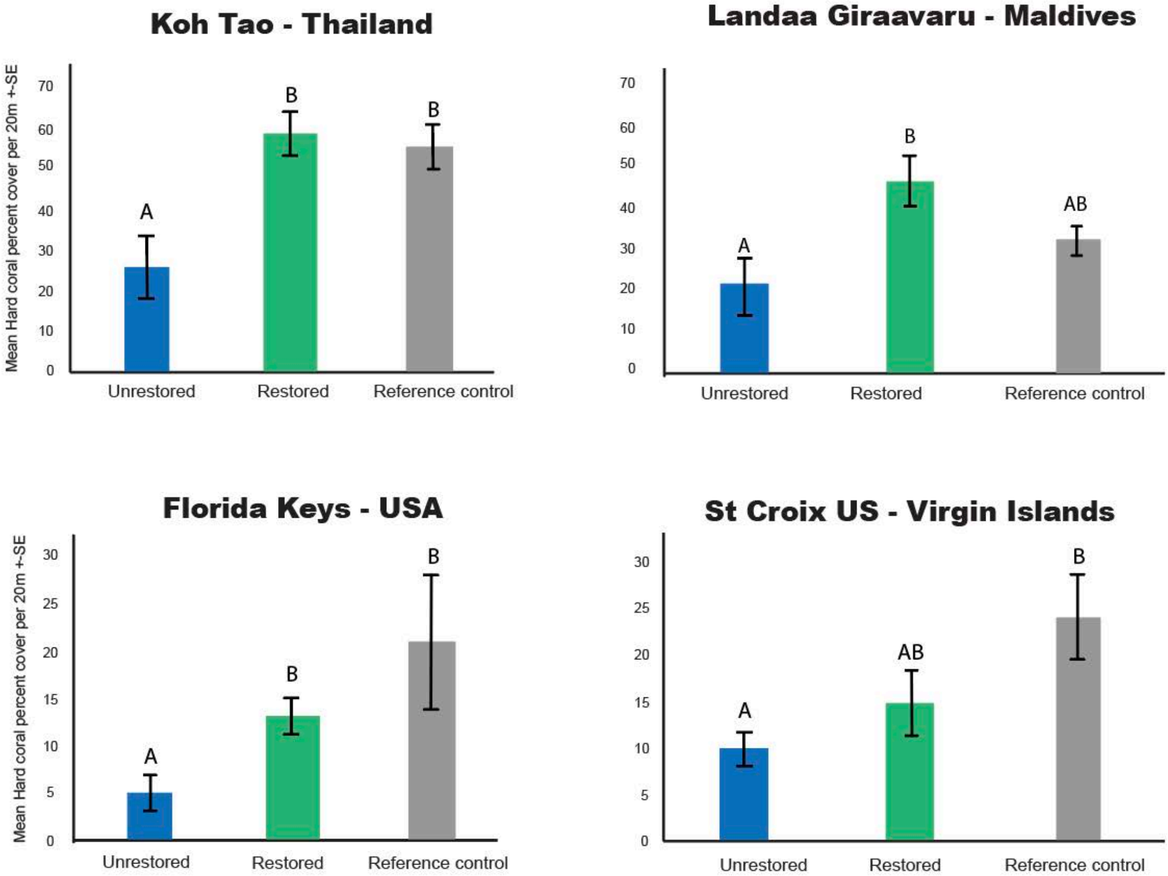


Figure 3.3 Mean percent cover of hard corals per 40m^2 belt transect (±SE) compared among treatments (unrestored, restored, reference control sites) at each of the four locations. Letters above each histogram indicate whether mean values differ significantly (different letters) or are statistically indistinguishable (same letters). n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

3.3.2 Structural complexity

Structural complexity was significantly higher at restored sites compared to unrestored degraded sites at all four locations (Figure 3.4, Table S3.2). In Koh Tao, structural complexity scores were two times greater at restored compared to unrestored sites (LM, F=23.18, p<0.001, Table S3.2), and 1.5 times greater at restored compared to reference control sites (GLM, p=0.0013, Table S3.2, Figure 3.4). At all three other locations, although structural complexity scores were 1.5

times greater at restored than at unrestored sites (Landaa Giraavaru LM, F=6.9, p=0.0014, Florida Keys LM, F=11.5, p=0.019, St Croix LM, F=19.4, p<0.001, Table S3.2), mean scores were highest at reference control sites (Figure 3.4).

Structural complexity scores at restored sites were consistently above the overall average score of structural complexity for any reef (2.5 out of 5), while scores at unrestored sites were consistently below 2.5 (Figure 3.4).

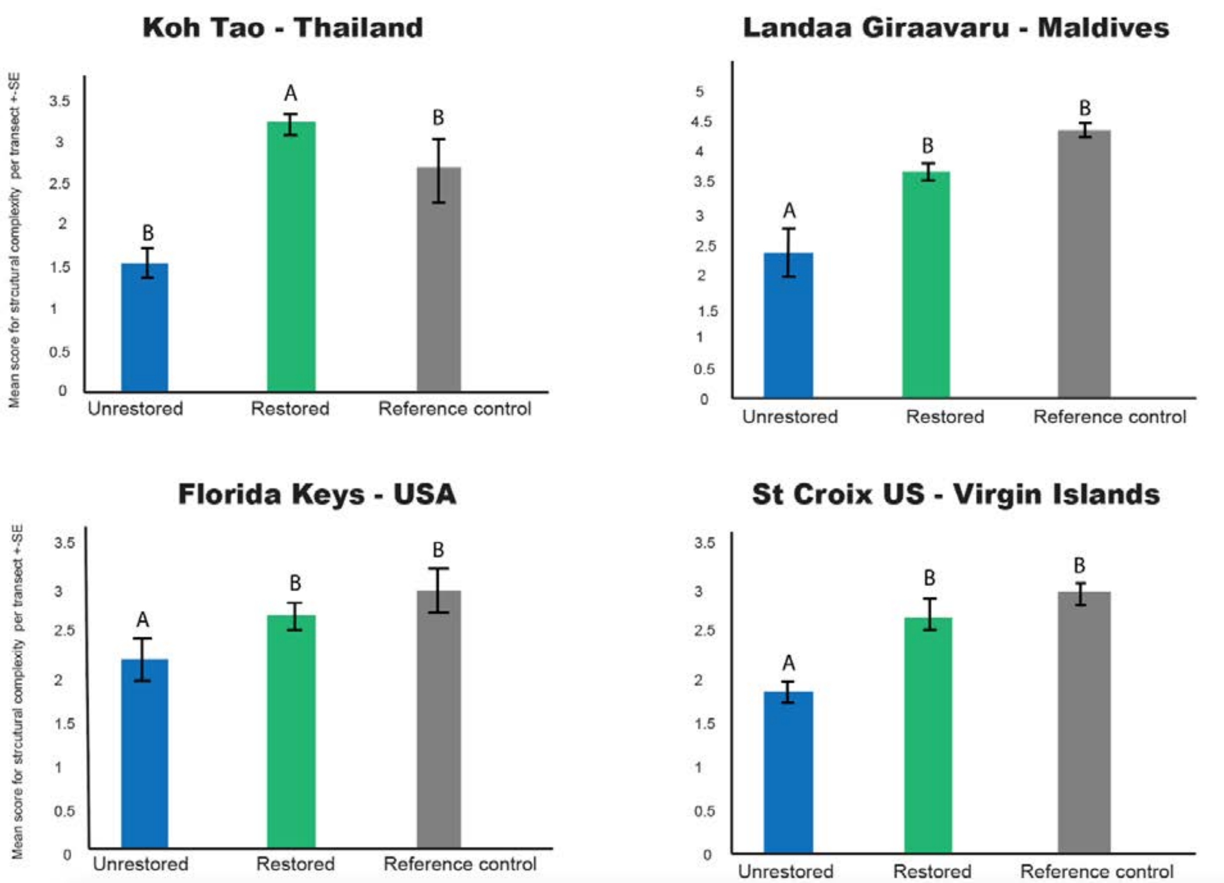


Figure 3.4 Mean structural complexity scores (±SE) compared among treatments (unrestored, restored, reference control sites) at each of the four locations. Letters above each histogram indicate whether mean values differ significantly (different letters) or are statistically indistinguishable (same letters). n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

3.3.3 Number of coral juveniles

This indicator was only valid for Koh Tao and Landaa Giraavaru because juvenile coral colonies were not detected in high enough abundance in the Florida Keys or St Croix to have sufficient data for statistical analyses at these two locations.

In Koh Tao, mean abundance of juvenile corals was greatest at restored sites. Mean abundances were significantly greater at restored than at unrestored sites where no juveniles were recorded (Kruskal-Wallis, Chi-square=8.22, df=2, p=0.043, Table S3.3, Figure 3.5). In contrast, mean abundance of juveniles did not differ significantly between restored and control reference sites (Table S3.3, Figure 3.5). Overall, the mean number of juveniles recorded in Koh Tao was 5.7/40 m^2, with abundances differing among restored sites according to the artificial structures used (Kruskal-Wallis, Chi-square=6.06, df=2, p=0.049, Table S3.4). The highest number of juveniles recorded were on concrete reef balls in Tanote Bay (Figure 3.6), and the lowest number recruited to the mix of steel frames and bottle nurseries in Chalok Bay (Figure 3.6).

In Landaa Giraavaru, mean abundance of coral juveniles did not differ among the three treatments (Kruskal-Wallis, Chi-square=0.825, df=2, p=0.66; Table S3.3, Figure 3.5). Over all sites and treatments, the mean number of juveniles observed was 8 juveniles/40 m^2.

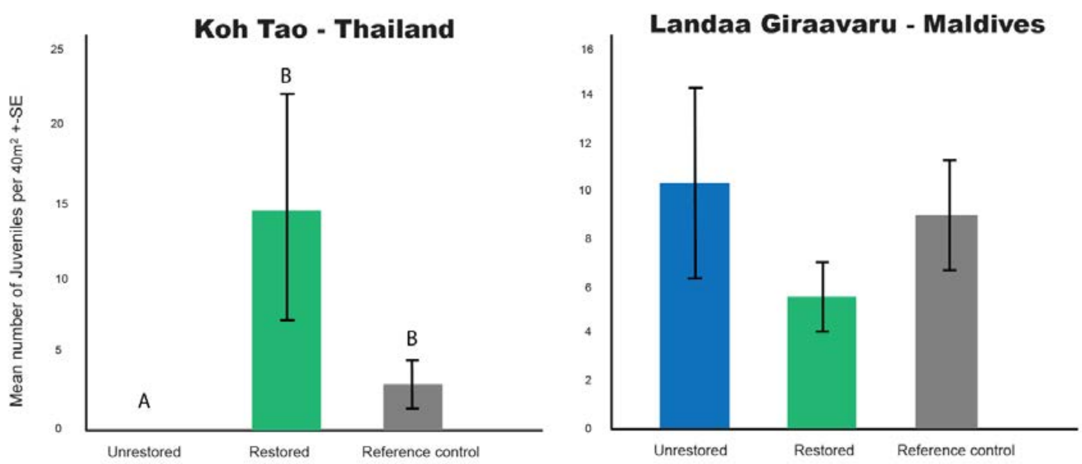


Figure 3.5 Mean number of juvenile corals counted per 40m^2 belt transect (±SE) compared among treatments (unrestored, restored, control reference sites) in Koh Tao (Thailand) and Landaa Giraavaru (Maldives). Letters above each histogram indicate whether mean values differ significantly (different letters) or are statistically indistinguishable (same letters). n=9 transects per treatment

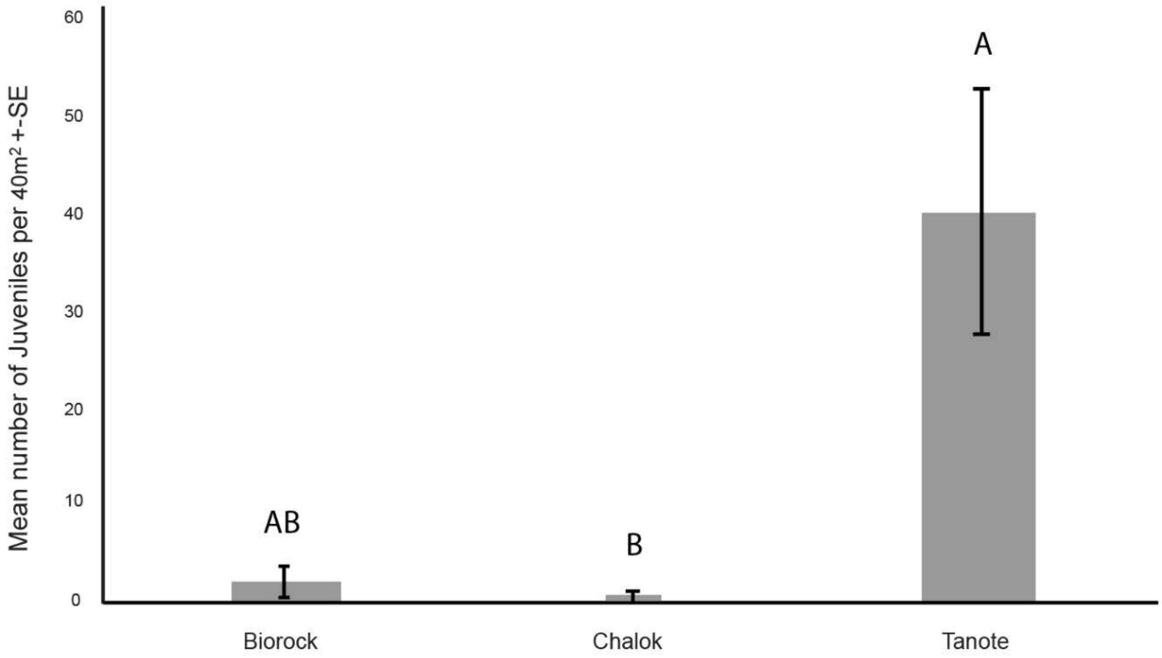


Figure 3.6 Mean number of juvenile corals counted per 40m^2 belt transect (±SE) compared among the three restored sites in Koh Tao (Thailand). Restoration designs varied among the three sites such that corals were only transplanted onto electrified steel frames at the Biorock site, onto steel frames and glass bottles in concrete in Chalok, and onto concrete reef balls in Tanote. Letters above each histogram indicate whether mean values differ significantly (different letters) or are statistically indistinguishable (same letters). n=9 transects per treatment

3.3.4 Coral generic richness

Coral generic richness was improved at restored compared to unrestored in Koh Tao only (GLM, RD=13.2, p=0.0352, Table S3.5, Figure 3.7). In both the Florida Keys and St Croix, coral generic richness was similar across all treatments at all locations (Table S3.5). In Landaa Giraavaru, coral generic richness was significantly lower at the restored sites compared to both unrestored (GLM, RD=29.2, p=0.0015) and control reference sites (GLM, RD=29.2, P<0.001), (Table S3.5, Figure 3.7).

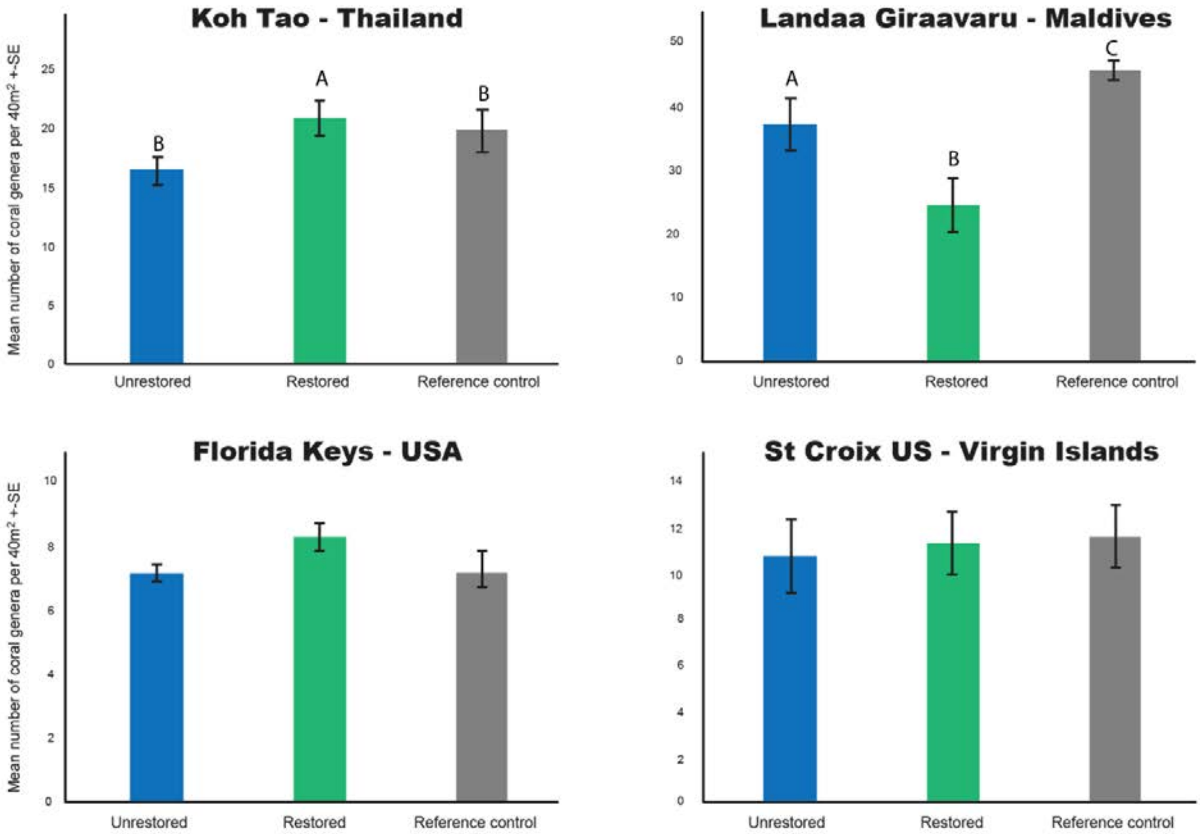


Figure 3.7 Mean number of coral genera per 40m^2 belt transect (±SE) among treatments (unrestored, restored, reference control sites) at each of the four locations. Letters above each histogram indicate whether mean values differ significantly (different letters) or are statistically indistinguishable (same letters). n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

3.3.5 Coral health

Coral health varied among treatments and locations. In Koh Tao, unrestored sites had a four-fold higher prevalence of unhealthy coral colonies compared to restored and control reference sites (GLM, RD=1534, p<0.001, Table S3.6), driven by a four-fold higher prevalence of coral colonies with signs of compromised health (GLM, RD=4.35, p<0.001, Table S3.8, Figure 3.8). The prevalence of diseased corals and of colonies with signs of predation did not differ among treatments (Figure 3.8, Table S3.7). Signs of predation in Koh Tao were primarily identified as feeding scars from *Drupella* snails and crown-of-thorns starfish (COTS).

In Landaa Giraavaru, the prevalence of unhealthy coral colonies was consistently over 80% of all colonies in all treatments. The overall high prevalence of unhealthy corals was driven by a high (62.4%) mean prevalence of bleached corals. Disease prevalence was also twice as high at restored sites compared to control reference sites (GLM, RD=6.03, p=0.025, Figure 3.8, Table S3.7).

In the Florida Keys, disease prevalence was highest at reference control sites, 1.5 times more so than at restored sites (GLM, RD=1.64, p=0.028, Table S3.7), and 2.8 more so than at unrestored sites (GLM, RD=1.64, p=0.006, Table S3.7, Figure 3.8). Only restored sites had signs of predation, making the prevalence of predation scars significantly higher at these sites compared to both unrestored (Kruskal-Wallis, Chi-square=21.034, df=2, p=0.038, Table S3.9) and reference control sites (Kruskal-Wallis, Chi-square=21.034, df=2, p=0.038, Table S3.9, Figure 3.8).

In St Croix, restored sites had a higher prevalence of diseased colonies than unrestored (GLM, RD=0.41, p<0.001, Table S3.7) and control reference sites (GLM, RD=0.41, p=0.037, Table S3.7), and higher prevalence of compromised colonies than control reference sites (GLM, RD=0.92, p<0.001, Table S3.8, Figure 3.8). Restored sites were also the only sites at which I observed signs of predation (Figure 3.8). Signs of predation in both the Florida Keys and St Croix were dominated by scars from flatworms, and fish bites.

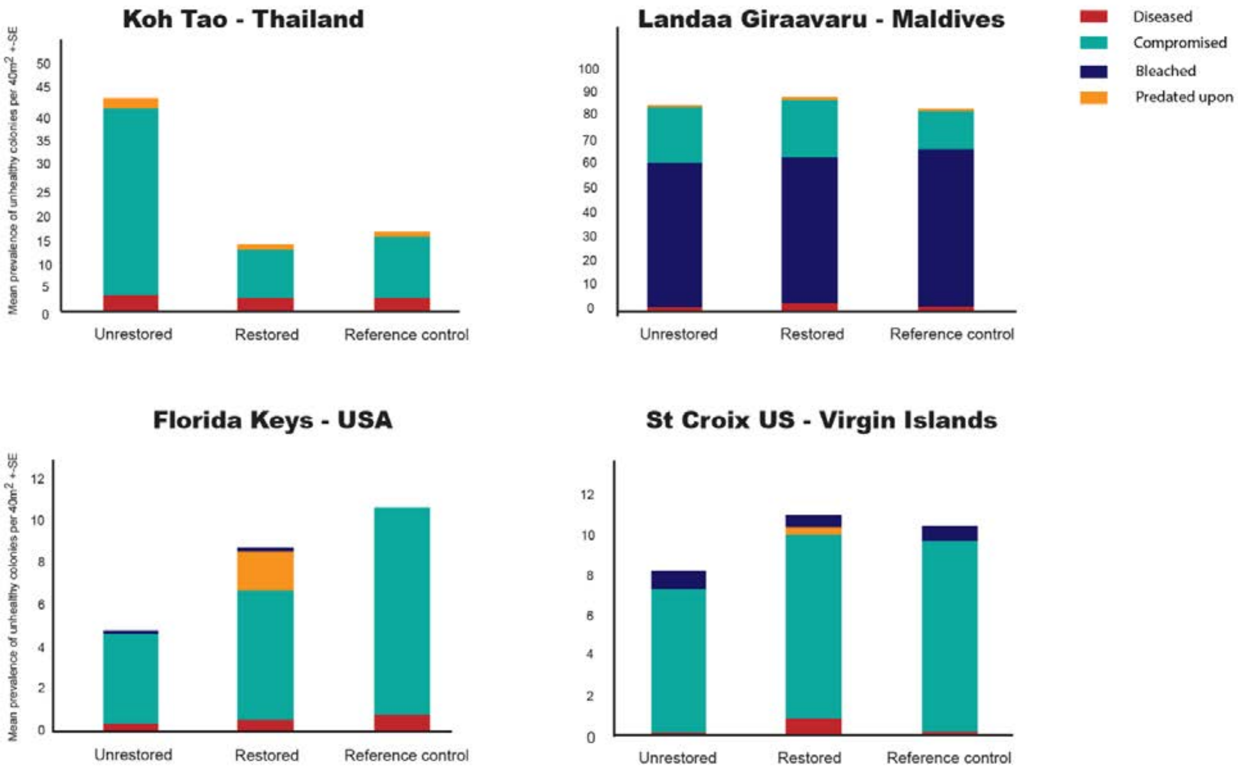


Figure 3.8 Mean prevalence of corals in four health categories representing unhealthy states (corals with signs of disease, bleaching, predation, or other signs of compromised health) per 40m^2 belt transect compared among treatments (unrestored, restored, reference control sites) at each of the four locations. n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

3.3.6 Composition of the coral assemblages

In Koh Tao, the composition of the coral assemblages was significantly distinct at the control reference sites compared to both restored and unrestored sites (ADONIS, CR to R F=3.64, p=0.014; CR to UR F=4.52, p=0.008, Table S3.10, Figure 3.9). There was also a significant effect of site on the composition of the coral assemblages (ADONIS, F=5.67, p=0.001). ADONIS on the NMDS detected differences in hard coral cover (ADONIS, F=6.27, p=0.001), structural complexity (ADONIS, F=5.56, p=0.002), coral diversity (ADONIS, F=2.83, p=0.026), and coral health (ADONIS, F=2.53, p=0.036) that distinguished coral assemblages at the control reference sites. Disease prevalence was the strongest factor separating coral assemblages at the restored sites (ADONIS, F=5.38, p=0.002), and the prevalence of indicators of compromised health distinguished the assemblages at the unrestored sites (ADONIS, F=2.36 p=0.022). Overall, coral assemblage composition at the restored sites was intermediate between those at the unrestored and reference control sites (Figure 3.9). Restored sites had four times more cover of corals in the family Acroporidae than both unrestored and reference control sites (Figure 3.10). Accordingly, the cumulative contribution of Acroporidae accounted for 75% of the differences between restored and unrestored sites (SIMPER). Sand dominated the benthos at unrestored sites, accounting for 47% (SIMPER, cumulative contributions) of the differences between unrestored and restored sites, and 38% of the differences between unrestored and reference control sites (SIMPER, cumulative contributions). Poritidae and Fungiidae were also more abundant at control reference sites than restored and unrestored sites (Figure 3.10).

In Landaa Giraavaru, the composition of coral assemblages at the restored sites differed significantly from the composition of assemblages at unrestored and control sites (ADONIS, R to UR F=3.33, p=0.15; R to CR F=3.78, p=0.005, Table S3.10). Coral assemblages were also significantly different at control compared to unrestored sites (ADONIS, F=2.29, p=0.045, Table S3.10). There was also a significant site effect on the composition of the coral assemblages (ADONIS, F=2.18, p=0.004). ADONIS analyses on the NMDS detected differences in structural complexity that distinguished the composition of the coral assemblages at reference control sites (ADONIS, F=3.84, p=0.009). Differences in the abundance of juvenile corals distinguished unrestored sites (ADONIS, F=3.3, p=0.008, Figure 3.9). Restored sites were characterised by higher cover of corals in the family Acroporidae and rubble at restored sites (Figure 3.10). Rubble contributed to 30% of the differences between restored and unrestored sites, and 72% of the difference between restored and control reference sites (SIMPER, cumulative contributions). Acroporidae contributed to 58% of the differences between restored and unrestored sites, and to 55% of the differences between restored and control reference sites (SIMPER, cumulative contributions).

In the Florida Keys, only unrestored sites had a distinct benthic community composition (ADONIS, UR to R F=3.52, p=0.014; UR to CR F=3.88, p=0.006, Table S3.10, Figure 3.9). There was also a significant site effect on the composition of the benthic community (ADONIS, F=3.88, p=0.001). ADONIS analyses on the NMDS detected differences in hard coral cover that distinguished the coral assemblages at restored sites (ADONIS, F=7.23, p=0.001). Differences in structural complexity (ADONIS, F=6.26, p=0.002) distinguished assemblages at reference control sites, and differences in the prevalence of healthy coral colonies (ADONIS, F=5.26, p=0.001) distinguished assemblages at unrestored sites (Figure 3.9). In terms of benthic composition, rocks, gorgonians, and Acroporidae were most influential in driving differences among treatments (SIMPER). The cover of corals in the family Acroporidae cover was nill at unrestored sites, and highest at control reference sites. Acroporidae accounted for 56% of the differences between unrestored and control sites, and 84% of the differences between unrestored and restored sites (SIMPER, cumulative contribution), and 64% between restored and control reference sites (SIMPER, cumulative contribution) (Figure 3.10). Rocks and gorgonians had the highest percent cover in unrestored sites (Figure 3.10). Rocks accounted for 32% of the differences between unrestored and restored sites, and 80% of the differences between unrestored and control reference sites (SIMPER, cumulative contribution). Gorgonian cover was twice as high in unrestored compared to both restored and reference control sites and thus accounted for 65% of the differences between unrestored and restored sites, and 29% of the differences between unrestored and control reference sites (SIMPER, cumulative contribution) (Figure 3.10).

In St Croix, the coral assemblages at restored sites differed significantly from those of both unrestored and control reference sites (ADONIS, R to UR F=6.96, p=0.001; R to CR F=3.5, p=0.004, Table S3.10). The coral assemblages at control reference sites were also distinct from those of the unrestored sites (ADONIS, F=3.15, p=0.017, Table S3.10). The composition of the benthic community also varied significantly among sites (ADONIS, F=3.49, p=0.001). ADONIS analyses on the NMDS detected differences in hard coral cover (ADONIS, F=4.53, p=0.003) distinguishing coral assemblages at control reference sites. Differences in structural complexity (ADONIS, F=5.45, p=0.002), and in the prevalence of diseased coral colonies (ADONIS, F=5.15, p=0.001) distinguished assemblages at restored sites. Differences in the prevalence of coral colonies with indicators of compromised health (ADONIS, F=4.08, p=0.003) distinguished assemblages at unrestored sites (Figure 3.9). In terms of benthic community composition, Acroporidae cover was 1.9 times that of restored sites than in reference control sites and Acroporidae were absent from unrestored sites (figure 3.10). Acroporidae therefore accounted for 71% of the differences between unrestored and restored sites (SIMPER, cumulative contribution). Astrocoeniidae were only present in control reference sites and accounted for respectively 69% and 65% of the differences in benthic community between restored and control reference sites, and between unrestored and control reference sites (SIMPER, cumulative contribution). The benthic community composition of unrestored sites was dominated by rocks and algae (Figure 3.10).

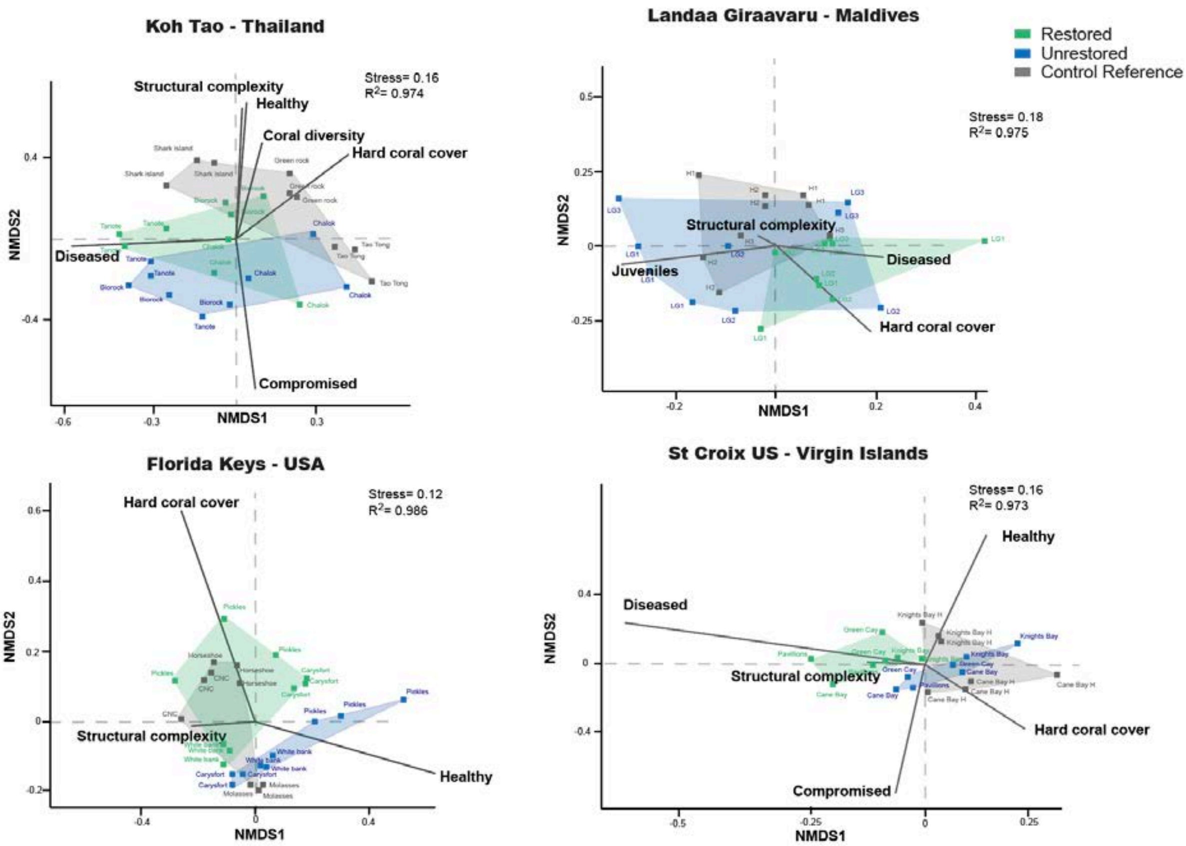


Figure 3.9 Differences in coral community composition among restored, unrestored and reference sites at four geographic locations, as represented by non-metric multidimensional scaling. Polygons represent coral assemblages in each treatment, where green polygons encompass restored sites, blue polygons encompass unrestored sites, and grey polygons encompass control reference sites. Coloured shading reflects the location of the respective set of sites in non-metric multi-dimensional scaling space. Vectors represent the influence of benthic attributes on the benthic community composition

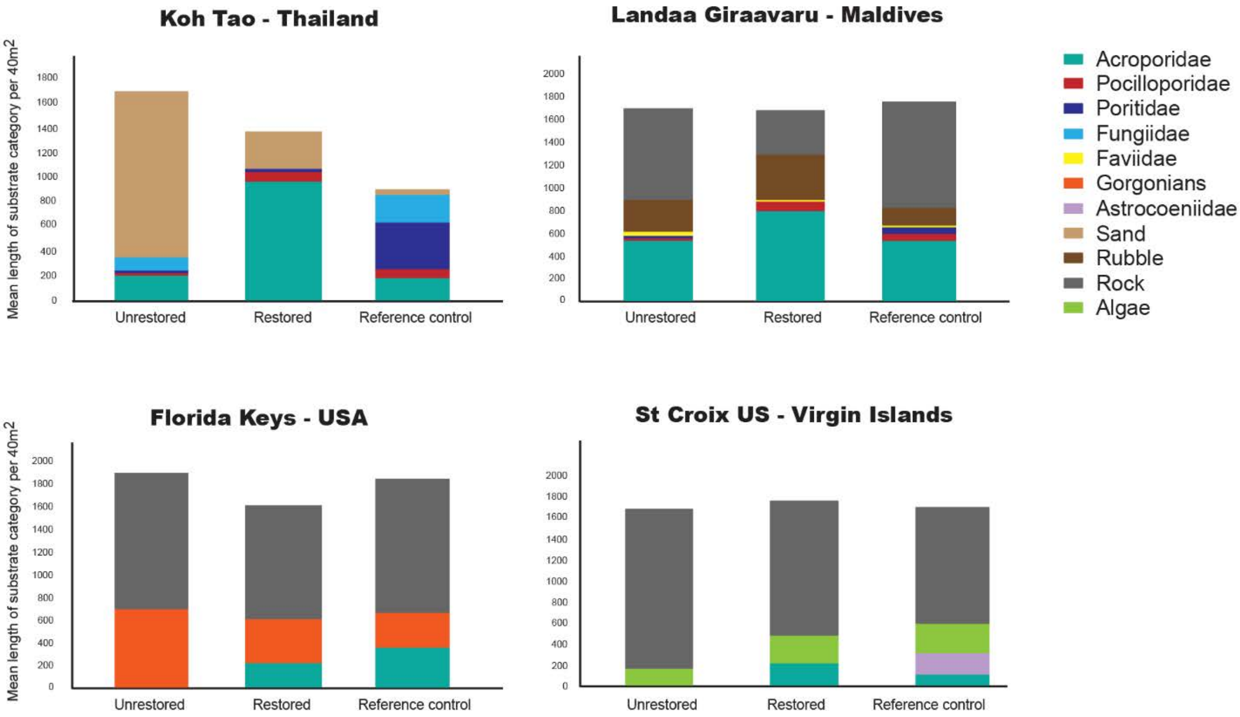


Figure 3.10 Comparisons of the mean cover of the most influential substrate categories (post- simper analyses) per 40m^2 belt transect among treatments (unrestored, restored, reference control sites) at each of the four locations. n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

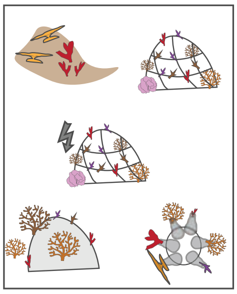
3.3.7 Summary and links with restoration designs

The effect of coral restoration on the five ecological indicators surveyed differed among the four study locations associated with different restoration designs (Table 3.1). Overall, all five indicators surveyed positively increased in restored sites in Koh Tao where the restoration design includes a mix of direct transplantation and a variety of artificial structures (steel frames, electrified steel frames, concrete reef balls, and glass bottles in concrete, Table 3.1). This combination of techniques led to the highest rate of increase in structural complexity, coral generic diversity, number of juveniles, and improved coral health at restored compared to unrestored sites of all study locations (Table 3.1).

The steel frames in Landaa Giraavaru also led to significant increases in hard coral cover and structural complexity at restored compared to unrestored sites (Table 3.1). Yet, the restoration design at this location also led to significant decreases in coral generic richness at restored sites (Table 3.1).

Direct transplantation was the only technique used in both the Florida Keys and St Croix. This technique resulted in consistent increases in hard coral cover, structural complexity, and coral generic diversity (Table 3.1). In the Florida Keys, the restoration design also led to five times greater hard coral cover at restored compared to unrestored sites, thus this metric had the greatest in the Florida Keys of all four study locations (Table 3.1). Conversely, increases in hard coral cover at restored compared to unrestored sites were the lowest in St Croix (Table 3.1). Finally, coral health was poorer in restored compared to unrestored sites in both the Florida Keys, and St Croix (Table 3.1)

Table 3.1 Summary table comparing the five ecological indicators surveyed at the four study locations with different restoration designs. Numerical values represent ratios of each metric at restored compared to unrestored sites. Coloured boxes represent the significance of the difference between restored and unrestored sites. Green denotes significant positive ratios, red denotes significant negative ratios; blue denotes non-significant differences

				
	Koh Tao - Thailand	Landaa Giraavaru - Maldives	Florida Keys - USA	St Croix - US Virgin Islands
Hard coral cover	+3.38*	+3.11*	+5.25*	+1.50
Structural complexity	+2.23*	+2.13*	+1.29*	+1.61*
Coral diversity	+1.26	-0.63*	+1.17	+1.06
Coral juveniles	+14.4*	+1	NA	NA
Coral Health	+1.57*	-0.94	-0.97*	-0.97*

3.4 Discussion

This study is the first to evaluate the long-term effect of coral restoration efforts on coral assemblages and to test the generality of outcomes across programs using differing protocols in a range of geographic locations. I found systematic increases in hard coral cover and reef structural complexity at restored compared to unrestored sites at all four locations surveyed. Moreover, multivariate analyses confirmed that outplanted corals had substantial impacts on local benthic communities, causing community composition at restored sites to resemble comparatively healthy reference communities more closely than unrestored communities. Patterns in the responses of other ecological indicators of reef resilience to restoration programs varied across locations, potentially reflecting variations in benthic assemblages and/or variations in response to different restoration methodologies.

3.4.1 Restoration increases coral cover and structural complexity

The doubling of hard coral cover at restored compared to unrestored sites at all locations except St Croix, where coral cover increased by 5%, indicates that the range of restoration techniques investigated here are effective strategies for restoring coral assemblages. Moreover, coral cover was higher in restored plots than at control reference sites following ten years of restoration at both Indo-Pacific locations (Koh Tao and Landaa Giraavaru). While coral cover remained highest at control reference sites in the Florida Keys and St Croix, the restoration goals of these two Caribbean programs were more focussed on growing and restoring endangered species of *Acropora (A. cervicornis* and *A. palmata)* (Johnson et al. 2011). Systematic increases in hard coral cover at restored sites are unsurprising, as corals fragments were actively planted at all four locations. However, results suggest that while corals may suffer post-transplant stress and mortality (Lirman et al. 2010, Forrester et al. 2012, 2014), restoration efforts at all four locations are substantive enough to have positive effects on coral cover over ten-year timeframes. Increased hard coral cover is a necessary first-step towards increasing reef resilience, increasing local breeding populations of corals, providing habitats for juvenile fish and invertebrates, and potentially preventing or at least mitigating phase-shifts towards algae-dominated systems (Hughes et al. 1994, Gardner et al. 2003).

Consistent significant increases in structural complexity at restored compared to unrestored sites at all four study locations suggest that both direct transplantation of coral fragments on the substrata and transplantation on artificial structures are effective in increasing reef relief at restored sites. In Koh Tao, where coral fragments are generally attached to artificial structures, structural complexity was doubled at restored compared to unrestored sites, and higher at restored compared to reference control sites. Although artificial structures were used in Landaa Giraavaru, structural complexity did not differ significantly between restored and reference sites, largely because of the high natural complexity of control reference reefs (mean structural complexity greater than 4 out of 5). Here, complexity represents the degree of reef relief (cf. Polunin & Roberts 1993) but does not specifically account for the number and sizes of holes and crevices present in the reef matrix, which may affect the abundance and diversity of fish and invertebrates (Hixon and Beets 1989). Given that the quality of reef complexity likely varies between artificial structures and natural reefs, further studies are needed to investigate the responses of fish and invertebrates to restoration in Landaa Giraavaru and elucidate how artificial structures affect the quality of reef complexity and associated reef organisms. In the Florida Keys and St Croix, the lack of difference in structural complexity between restored and reference control sites reflects that most of the complexity at these locations is provided by the presence or absence of thickets of branching *Acropora,* which are the targets of the restoration efforts. Overall, increases in the structural complexity of the degraded reef sites surveyed (to more than 2.5 out of 5) have important implications for reef resilience. High structural complexity accelerates recovery following disturbances (Graham et al. 2015), creates microhabitats that are refuges from bleaching (Hoogenboom et al. 2017), and can increase the abundance of protected surfaces upon which coral recruits can settle and grow.

3.4.2 The resilience potential of restored reefs varies among restoration programs

Despite increases in coral cover and structural complexity at restored sites, other critical indicators of reef resilience did not increase consistently in response to the restoration efforts. For example, higher densities of juvenile corals at restored compared to unrestored sites were only found in Koh Tao, and only on concrete reef

balls. It may be that the high surface rugosity of reef balls is conducive to coral larvae settlement (Edwards & Clark 1998, Miller & Barimo 2001). However, because Koh Tao was the only restoration program out of the four studied to use these structures, and they were only used at one out of the three restored sites, I am unable to distinguish between the potential contributions of site versus type of structure on the increased abundance of coral juveniles at this one site.
In Landaa Giraavaru, the lack of difference in juvenile coral density among treatments might be attributable to either the type of structure used (i.e., stainless-steel frame structures that are not conducive to larvae settlement), and/or the fact that reefs around the island are not limited by recruitment. Here, the average number of juveniles recorded across all sites (0.8/m^2) was much lower than coral recruit densities previously reported in the Maldives (2.5 to 18 ind/m^2, Edwards & Clark 1998), and in other regions of the world (4 to 80 ind/m^2, Connell et al. 1997, Glassom et al. 2006). However, these studies define coral recruits as any new corals colonising the restored sites (Edwards & Clark 1998), and use other survey techniques (e.g. recruitment tiles, Glassom et al. 2006). It is possible that methods used here, of only recording corals with a diameter <5cm in 2m-belt transects, may have limited the detection of coral recruits. This interpretation is supported by findings of similar densities of recruits in Lord Howe Island using the same methods (Hoey et al. 2011). The paucity of recruitment in both the Florida Keys and St Croix precluded investigating the effect of coral restoration on coral recruitment at these two locations, and further confirms that reefs in the Caribbean are severely limited in their ability to recruit new juvenile corals (Hughes & Tanner 2000, van Woesik et al, 2017).

Coral generic richness was a second indicator of reef resilience that was not consistently augmented by restoration programs. Coral restoration only positively affected coral generic richness in Koh Tao, where the restoration design explicitly aims to maximise the diversity of coral transplants. In the three other locations, targeted transplantation of specific corals meant that coral generic diversity was either lowest at the restored sites (Landaa Giraavaru) or indistinguishable from unrestored sites (Florida Keys, St Croix). In Landaa Giraavaru, coral transplants were dominated by fast growing, branching corals from the genera *Acropora* and *Pocillopora*, artificially boosting the density of these two genera at restored sites.

The lack of restoration effect on generic richness in the Florida Keys and St Croix was unsurprising given that restoration efforts target the two endangered species of *Acropora* (Johnson et al. 2011).

Finally, coral health, a third indicator of reef resilience that was not consistently improved by restoration, revealed location-specific patterns. Again, this indicator was improved only in Koh Tao, potentially because of the high level of maintenance by the NHRCP team. It is also likely that elevation of the corals slightly above the substrata on artificial structures prevented them from being smothered by sediments or algae. Unrestored sites had significantly higher prevalence of colonies with sediment damage and algal overgrowth (included in the other signs of compromised health category), corroborating this line of reasoning. It is noteworthy that there was no evidence that transplanted fragments are more susceptible to disease due to manipulation and injuries sustained in the process of attaching them to structures. In summary, results from Koh Tao suggest that planting corals above the substrata and maximising the diversity of corals transplanted are good strategies to maximise coral health at restored sites.

In Landaa Giraavaru, poor coral health in all treatments reflected that, at the time of the survey, the Maldives were experiencing mass coral bleaching. Corals at all survey locations were severely bleached regardless of the depth or restoration treatment. The overriding impact of thermal stress at the time of the surveys is a reminder that active intervention approaches like coral restoration are inadequate in the face of global climate-change associated disturbances. While bleaching was uniform across treatments, I did find a higher prevalence of diseased corals at restored and unrestored sites compared to control reference sites. These results were mostly due to brown band disease outbreaks affecting bushy and staghorn *Acropora*, which occurred in higher densities at the restored sites. Higher disease prevalence at restored sites could thus be linked to higher densities of *Acropora,* which are one of the more susceptible genera of corals (Willis et al. 2004) and were concurrently suffering from decreased disease resistance due to thermal stress (Bruno et al. 2007, Heron et al. 2010, Caldwell et al. 2016). Another factor contributing to increased disease prevalence at restored sites could have been injuries caused by the involvement of unskilled tourists in the program/ attaching fragments to artificial structures. Breakage and injury are known to increase disease prevalence in coral populations (Page et al. 2009, Lamb et al. 2014).

In the Florida Keys, the prevalence of both disease and predator scars varied among restoration treatments. Coral disease prevalence was highest at reference control sites, potentially because of high densities of *Acropora* combined with no active maintenance of natural reef areas, and the overall history of disease-related loss of Caribbean species of *Acropora* (Aronson & Precht 2001, Williams & Miller 2012). The prevalence of predation scars, on the other hand, was highest at the restored sites, likely reflecting fire-worm predation on freshly planted *A. cervicornis* (Johnston & Miller 2014, Miller et al. 2014).

In St Croix, restored sites were again the only sites to experience coral predation at that location. Together with higher disease prevalence, restored sites had overall lower coral health than either unrestored or control reference sites. Results from both the Florida Keys and St Croix raise questions about whether Acroporidae are good candidates for coral restoration in the Caribbean. While the two Caribbean programs are meeting their goal of increasing *Acropora* cover at restored sites (NOAA Acropora recovery plan, National Marine Fisheries Service 2015), focussing on this genus might not lead to successful long-term outcomes in terms of reef resilience and enhanced reef-related ecosystem goods and services. Maximising the diversity of coral transplants at these locations might help harness natural ecological processes that decrease competition between and predation upon freshly transplanted corals, and therefore optimise the long-term outcomes of the restoration process (Shaver & Siliman 2017, Ladd et al. 2018).

3.4.3 Coral restoration influences the composition of the benthic community

Restoration affected the composition of benthic communities at all four locations. Increases in hard coral cover and structural complexity were significant factors influencing benthic community composition at all locations except Landaa Giraavaru. In Landaa Giraavaru and St Croix, the composition of the benthic community at restored sites was distinct from that of both control and unrestored sites. In Koh Tao, the composition of the benthic community at restored sites only differed from that of control reference sites, and the Florida Keys, the composition of benthic communities did not differ between restored and reference control sites. These results highlight that the coral restoration efforts affected a much wider scale than that of the coral transplants. Restoration methodologies including the use of artificial structures, to the identity of the coral transplants, site selection, and transplant density all require careful consideration in terms of their impact on local benthic communities. Site selection, in particular, is increasingly recognised as a very important factor for maximising the outcomes of the restoration efforts (Johnson et al. 2011, Schopmeyer et al. 2017, Shaver & Siliman 2017, Ladd et al. 2018). Comparisons of benthic community composition between restored and control reference sites are useful indicators of whether site-selection was appropriate. One could argue that the control reference sites surveyed in this study are some of the most resilient sites in the area, as they had a similar history of disturbances and yet fared better than other sites. Similarities in benthic community assemblages at restored and control reference sites in the Florida Keys suggest that the restoration efforts increased the resilience of benthic communities at these sites, and that site selection for the restoration effort was indeed appropriate. The capacity of restoration efforts to affect the restored sites at the scale of benthic community assemblages is an important result that supports findings from Chapter 2 (section 2.2) that characterising restoration effectiveness requires broad, reef-scale considerations.

3.4.4 Limitations and further research

The sampling design for this chapter did not allow for comparisons of restoration effectiveness among the four programs because the type of restoration design, the level of maintenance, and the age of restored plots all varied among the four locations. Also, in three of the programs, only one type of restoration design was used (i.e., metal frames in the Maldives, midwater nurseries at both Caribbean locations), precluding meaningful comparisons of restoration effectiveness between designs. Further research on patterns in restoration effectiveness among different types of artificial structures or between artificial structures versus direct transplantation onto reef substrata at one location would complement my broad geographic comparisons. Furthermore, data for this chapter were collected at the genus- rather than species-level so that restoration managers could easily replicate my monitoring program. However, species-level data would provide greater insights into changes in coral diversity patterns and impacts on coral health, especially for restoration programs focused on restoring endangered coral species (e.g., *Acropora* species in the Caribbean).

3.5. Conclusions

In this Chapter, I reveal that planting corals on degraded reefs results in consistent, long-term increases in hard coral cover and reef structural complexity, which are necessary steps in the recovery of degraded reefs, a major goal of restoration programs. In the Florida Keys and St Croix, where all corals transplanted are critically endangered species of *Acropora*, increased hard coral cover and structural complexity at restored sites meet the primary objective of protecting the two endangered coral species, enabling them to resume their structuring role on Caribbean reefs. Other indicators varied among programs and restoration designs. Juvenile coral densities had the greatest increases at restored sites where concrete artificial structures were used (Koh Tao), and coral generic richness increased the most where the restoration design explicitly aimed to maximise this metric (Koh Tao). Coral health was best at restored sites where corals where planted off the reef substrata and regularly maintained to remove predators. In summary, the potential for coral restoration efforts to increase coral reef resilience in the long-term is thus promising, but they should focus more carefully on maximising coral generic richness, as well as planting corals off the substrata or in low-predation areas to maximise coral health at restored sites. In Chapter 4, I further investigate the effect of coral restoration on the fish abundance and diversity at these four established coral restoration programs.

CHAPTER 4

Characterising the effectiveness of coral restoration programs: comparing the fish response to restoration in four reef regions

4.1 Introduction

Coral restoration is increasingly used as a reef management strategy to combat loss of coral cover in the face of rising anthropogenic and environmental disturbances. In Chapter 2, I have demonstrated that while objectives of coral restoration align closely with principles of ecological and social resilience (section 2.2), current measures of restoration outcomes are limited to short-term assessments of the biological response of coral fragments to transplantation (section 2.3). Better informing reef managers on how restoration can be used as a tool to improve reef resilience necessitates a better understanding of the effect of coral restoration on reef structure and function.

In particular, it is a common assumption that coral restoration efforts will result in an increase in both the abundance and diversity of reef fishes, thereby improving ecosystem function and restoring some ecosystem services. Yet, fish responses to coral restoration efforts specifically are scarcely documented (Cabaitan et al. 2008, Ferse 2008, Mbije et al. 2013, Huntington et al. 2017). Fish are critical components of reef resilience following the paradigm that increased fish, and especially herbivore biomass, controls algal growth on degraded reefs therefore preventing shifts from coral to algal dominated reefs (Burkepile & Hay 2010; Heenan & Williams 2013, Ladd & Collado-Vides 2013). Fish are also involved in symbiotic relationship with coral colonies, where fish-derived services directly promote the growth of coral colonies at small scales, through excreted nutrients and cycling, reduced corallivory, and enhanced water flow and tissue aeration (Chase et al. 2014, Shantz et al. 2014). Increased fish biomass is also linked to social resilience with increased tourism and fisheries opportunities (McClanahan et al. 2012; Maynard et al. 2015). Improving the condition of fish communities on degraded reef systems is thus a critical management priority (Maynard et al. 2017) and the potential of coral restoration to aid the process requires more investigation.

Artificially increasing coral cover and structural complexity in coral restoration efforts might increase the abundance, biomass and diversity of associated reef fish community in a number of ways. First, live coral cover is critical recruitment habitat for more than two-thirds of reef associated species (Jones et al., 2004) and directly influences juvenile and adult stocks of coral dependent fish species (Feary et al. 2007; Wilson et al. 2008, Cole et al. 2008, Coker et al. 2013). Thus, where coral restoration efforts increase total live cover, an increase in abundance of fish might be expected. Second, the structural complexity of benthic habitat often positively influences the abundance and diversity of fish communities (Wilson et al. 2007, Richardson et al. 2017). This occurs via provision of shelter and as the diversity of spatial niches for living is increased (Hixon & Beets 1989). Where restoration efforts increase the topographic complexity of a reef, positive impacts on fish communities are to be expected. However, the nature of fish relationships to the benthos is frequently species-, size- and site-specific.

Fish with greater dependence on benthic habitats for food or shelter are expected to have stronger responses to structural changes of the benthos than those that are less dependent (e.g. transients). For example, restored sites may act as fish nursery areas recruiting juvenile fish, especially juvenile damselfishes attracted to branching coral species (Yap 2009, Shaish et al. 2010b, Agudo-Adiani et al. 2016), but colonisation by larger adult fish may be more dependent on the type of habitat structure provided by the restoration effort (Hixon & Beets 1989). The colonisation of fish of different size-classes to the restored sites is thus likely to follow complex ecological succession patterns and requires long-term considerations. A restored site may thus start as a nursery area, with an initial high abundance of small fish and develop a more diverse and complex fish community over time as coral transplant grow and coral cover and structural complexity increase.

The design of the coral restoration effort is likely to play an important role in the direction and characteristics of the fish response. Previous studies that have looked at the response of fish assemblages to coral restoration have found quite mixed responses (e.g. Ferse 2008, Mbije et al. 2013, Huntington et al. 2017), with variations attributed to coral transplant density and size (Agudo-Adiani et al. 2016, Huntington et al. 2017), and the state of the existing reef fish community at each site (Raymundo et al. 2007, Ferse 2008, Mbije et al. 2013, Huntington et al. 2017). Positive responses of fish communities to coral restoration were also often associated with the use of cement blocks as artificial structures for transplantation (Edwards & Clarke 1993, Carr & Hixon 1997, Fadji et al. 2012). Elucidating how fish respond to coral restoration efforts necessitates comparing fish assemblages associated with different types of restoration strategies (e.g. use of artificial reef structures versus direct transplantation on the reef substrata).

The location of the restored sites may also influence the fish response to restoration. Spatial characteristics of the restored sites such as their location on the reef (e.g. depth) (Srinivasan 2003), proximity to nursery areas (e.g. mangroves and/or seagrass) (Mumby et al. 2004, Dorenbosh et al. 2007), and proximity to healthy areas (Huntington et al. 2017) are all likely to influence the characteristics and magnitude of fish colonisation patterns. Increasing the understanding of how fish communities respond to coral restoration efforts across different reef regions, and different restoration designs is thus critical to better assess the large-scale and long-term effectiveness of coral restoration and adapt coral restoration design to maximise the potential to enhance reef resilience.

In this chapter, I ask whether long term restoration efforts have made any difference to the reef fish communities. Using the four programs described in Chapter 3 (section 3.2), I evaluate the characteristics of fish communities after eight to ten years of restoration efforts, determining whether or not the work has influenced reef fish assemblages and in what manner. I also explore which restoration methodologies most affect fish community abundance and composition.

I have the following hypotheses:
1: Fish communities will have responded to restoration efforts, showing higher overall abundance at restored, compared to unrestored sites. These responses will be linked to differences in benthic assemblages that have occurred because of restoration (Chapter 3, section 3.3).

2: Fish assemblages at the restored sites will have compositional structures more similar to control reference sites than unrestored sites, indicative of a restoration effect.
3: There will be size-specific differences in the responses of fish assemblages to restoration. In particular, small fish will respond strongly, with a higher abundance of small (<10cm) fish at restored than unrestored sites and strong compositional differences among treatments. Differences in abundance and composition of medium and larger bodied fish communities will be minimal and/or quite variable among treatments.
4: There will be a more positive response of fish assemblages (i.e., in abundance and composition) at locations where both structural complexity and coral cover have been increased.

Ultimately, I aim to discern which coral restoration designs yielded the strongest responses of the fish community in order to provide some guidance for reef managers who are using coral restoration to improve the status of reef fish communities.

4.2 Methods

4.2.1 Study sites and survey design

The fish surveys were carried out at the same four study sites described in Chapter 3 (section 3.2.1). As a reminder, each program has a specific coral restoration strategy: In Koh Tao, Thailand, the New Heaven Reef Conservation Program uses a mix of different restoration structures and direct transplantation; in Landaa Giraavaru, the Reefscapers program uses steel-framed dome structures to which they attach coral fragments; in the Florida Keys, USA, and St Croix, US Virgin Islands, the Coral Restoration Foundation and The Nature Conservancy, directly transplants coral fragments back onto the reef (Chapter 3, Figure 3.1).

Fish surveys were carried out on the same transects as the one used for the benthic surveys (See Chapter 3, section 3.2.1). At each location, reef fish data were compared among replicate restored sites (R), unrestored control sites (UR), and control reference sites (CR). Restored sites were sites at which coral fragments had been transplanted, either directly on the substrata or onto artificial structures; Unrestored control sites were sites directly adjacent to the restored sites where no coral fragments had been transplanted; and control reference sites were relatively undisturbed sites in the area on which no corals had been transplanted either. A minimum of three replicate sites were surveyed for each of the three treatments (R, UR, CR) at each location, except at St Croix, where the extent of appropriate undisturbed reef area was so small that I could only survey two control reference sites. Thus, three restored sites, three unrestored sites, and three healthy reference sites were surveyed at all locations (except for the two CR sites at St Croix). In addition, a fourth restored site and a fourth unrestored site were surveyed in St Croix.

4.2.2 Data collection

Reef fish and benthic variables were surveyed concurrently at all sites. Fish communities were surveyed along three replicate 20 x 5m belt transects per site. Following the fish counts, benthic variables of benthic cover, structural complexity and coral health categories were subsequently recorded along the same 20m transect lines through both line intercept transect method and 2m belts. Three replicate 20m transect were used per treatment in Koh Tao, Landaa Giraavaru, and the Florida Keys, for a total of 180m surveyed per treatment at each of these locations. In St Croix, the restored area was too small for three replicate 20m transects, thus two replicate 22.5m transects were surveyed at each of four R and four UR sites (i.e.,180m surveyed per treatment) to match the overall areas surveyed at other locations.

All fish observed were identified to the family level and assigned to one of the following size categories: 0 to 5cm, 5 to 10cm, 10 to 15cm, 15 to 20cm, 20 to 30cm, 30 to 60cm, 60cm+. Fish were counted along three 20x5m belt transects at each site. Size classes were later re-grouped into small (<10cm), medium (10 to 20cm), and large fish (over 20cm) for statistical analyses. Data was collected concurrently on attributes of the benthic community (e.g. benthic cover, structural complexity, coral health categories, coral generic richness, coral juveniles) at each of the site over the same transects. Detailed results from the benthic survey are available in Chapter 3 (section 3.3).

4.2.3 Data analysis

All data were analysed using R (Version 3.4.1). The analyses described below were applied to all four locations separately. Given the large geographic differences in locations, and the inherent differences in biodiversity and abundance of coral reef communities among geographic regions, the summative results among locations are only compared descriptively.

Fish counts

General Linear Models were used to compare the differences in fish abundance among treatments (R, UR, CR) at each location. Firstly, I investigate whether there is a difference in total fish abundance (per 100m2) among treatments and secondly whether the number of fish per size class differs among R, UR and CR sites (i.e., are there more, smaller fish in R sites than UR sites?). Treatments (R, UR, and CR) were fixed while sites were treated as random factor. Both additive and multiplicative models were run with Poisson and Negative binomial which are most appropriate for count data, and the best model was chosen through AICc model selection, with the best model having the lowest AICc score. Assumptions for model validity were checked through QQ plots and residual plots, as well as calculations of dispersion and R^2 values. Tukeys' contrast pairwise comparisons were performed to identify differences among treatments and sites. Linear models were used to test the interaction between treatments and sites.

Composition of the fish community

Multivariate analyses were used to assess potential differences in the familial composition of assemblages among treatments, per location. In particular I hypothesised that composition at restored sites will be more similar to reference than unrestored sites indicative of a positive restoration effect. Prior to analysis, all fish and benthic data were transformed using Wilcoxsins's double transformation with fourth root. I then created distance matrices based on "Bray-Curtis" dissimilarity indices as these are good at detecting ecological gradients (Faith et al. 1987), and applied non-metric Multidimensional scaling (nMDS) to the transformed dataset. The validity of nMDS was checked through the R^2 value of the linear and non-linear fit. Benthic cover data were overlaid on the nMDS and ADONIS tests (multivariate ANOVA based on dissimilarities) were used to explain the contribution of benthic variables to the differential composition of the fish community, at the family level. Benthic variables included hard coral percent cover, structural complexity (graded from 0 to 5 with 0 being very low complexity as per Polunin & Roberts 1993), density of Acroporidae and branching corals per $40m^2$, as well as the density of gorgonians for the Caribbean sites (Florida Keys and St Croix), and coral generic richness. ADONIS tests were also used to explain differences in fish assemblages among sites, and among treatments for total fish abundance, and for fish abundance among the three size classes (small, medium, and large). Pairwise ADONIS tests were performed to identify differences in fish community assemblages among treatments. Finally, SIMPER analysis evaluated how much each fish family contributed to differences in the abundance and assemblage composition among treatments, for each of the three size classes.

Effect of restoration design

To summarise the apparent effect of restoration efforts on fish assemblages, I calculated ratios of mean total fish abundance at restored versus unrestored sites per location, and also for each size class (small, medium, and large). The resulting ratio of differences were then assessed qualitatively against the different types of restoration designs used at each location, as well as against the restoration effects on the benthic assemblages observed in Chapter 3 (section 3.3).

4.3 Results

4.3.1 Total fish counts

The mean abundance of fish differed among treatments at each location but not consistently or significantly (Figure 4.1). In Koh Tao, fish were most abundant at the restored sites, with twice as many fish at the restored compared to unrestored sites, however this difference was not statistically significant (GLM, Residual Deviance (RD)=103.7, p=0.259 NS, Table S4.1, Appendix S4). In St Croix, restored sites also had 1.2 times more fish compared to unrestored sites (Figure 4.1), but again the difference was not significant (GLM, RD=76.4, p=0.922 NS, Table S4.1). In Landaa Giraavaru, the Florida Keys, and St Croix, the control reference sites held the most fish (Figure 4.1). In both Landaa Giraavaru and the Florida Keys, the restored sites had the fewest fish. At each location differences in fish abundance among treatments were not statistically significant (Table S4.1).

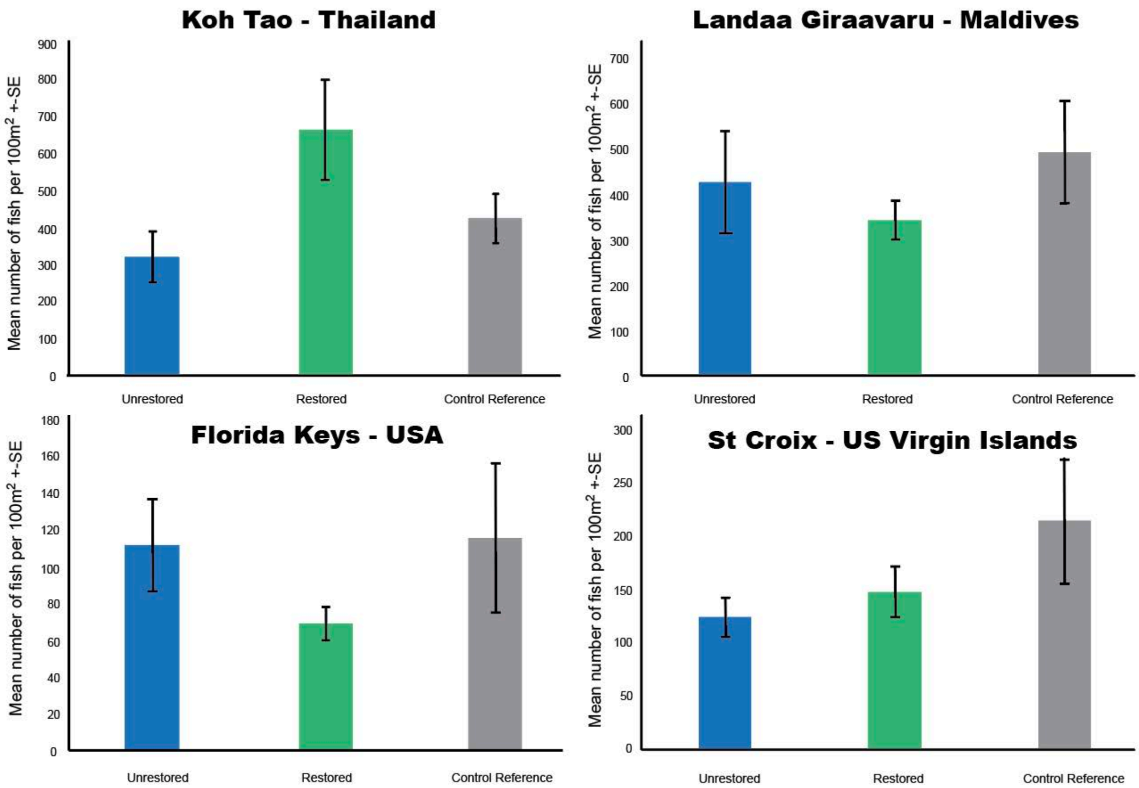


Figure 4.1 Mean number of fish observed per 100m^2 transect (±SE) at all four locations in unrestored, restored, and reference control sites. n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

The total number of fish also did not vary among sites in Koh Tao, Landaa Giraavaru, nor St Croix (Figure S4.1, Table S4.2), or among sites within treatments (LM, Koh Tao F=0.5946, p=0.7793; Landaa Giraavaru F=0.9797, p=0.4589; St Croix F=0.07386, p=0.6719). In the Florida Keys however, the fish abundance varied significantly among sites within treatments (LM, F=6.628, p<0.001), being two to three times more abundant at Molasses reef and White Bank unrestored reef than at any other reef and lowest at CNC reef (Figure S4.1, Table S4.2).

4.3.2 Fish counts by size

The effect of coral restoration treatment on fish abundance differed among size classes and the response per size class differed among locations (Figure 4.2).

Small fish (< 10cm TL)

Small fish only responded to the restoration treatment in Koh Tao, and not in other locations. There, small fish were most abundant at the restored sites with 2.4 times more small fish at restored compared to unrestored sites (GLM, RD=28.12, p=0.00198, Table S4.3, Figure 4.2), and 1.6 times more small fish at the restored compared to reference control sites (GLM, RD=28.12, p=0.14 NS, Table S4.3, Figure 4.2). In St Croix, small fish were most abundant at the reference control sites with about twice as many small fish at control sites compared to both unrestored (GLM, RD=1.16, p=0.009, Table S4.3), and restored sites (GLM, RD=28.12, p=0.07 NS, Table S4.3, Figure 4.2). In Landaa Giraavaru and the Florida Keys there was no difference in the number of small fish among treatments (Table S4.3, Figure 4.2).

Medium fish (10-20 cm TL)

Medium sized fish did not appear to respond positively to restoration treatments anywhere (Figure 4.2). In fact, the medium sized fish at restored sites were > 50% fewer than those seen at unrestored sites, at three locations. In Koh Tao, there were 3 times more fish at unrestored compared to restored sites (GLM, RD=28.76, p=0.0193, Table S4.3, Figure 4.2) with the latter populations also slightly less than the reference sites. In Landaa Giraavaru, the unrestored sites had 2.7 times more fish than restored sites (GLM, RD=27.16, p=0.0481, Table S4.3, Figure 4.2) and 3 times more than the reference sites (GLM, RD=27.16, p=0.0069, Table S4.3, Figure 4.2). In the Florida Keys there were two times less fish at restored sites than unrestored or reference control sites but the difference was not significant (Table S4.3, Figure 4.2). St Croix was the only location where medium fish were not substantively fewer at restored sites. Here there was a similar number of fish at restored and unrestored sites and significantly less (2.5 –2.8 fold less) in reference control sites (Table S4.3, Figure 4.2).

Large Fish (> 20cm TL)

The mean number of large fish (>20cm) observed on transects was very low overall ranging from 0 to a maximum of 147 fish per transect, and less than two individuals on average in Landaa Giraavaru. Similar to medium sized fish, large individuals appear to respond negatively to restoration treatments, with fewer fish at restored compared to unrestored sites in all location except St Croix (Table S4.3, Figure 4.2). In Koh Tao large fish were similarly lower at restored sites than unrestored and control reference sites but not significantly so (Table S4.3, Figure 4.2). In Landaa Giraavaru only 16 large fish were observed in total. Of these 11 occurred at the unrestored sites. In the Florida Keys, there were six times more fish at unrestored sites than at restored sites (GLM, RD=29.4, p=0.022, Table S4.3) and 12 times more large fish at reference control sites than at restored sites (GLM, RD=29.4, p=0.0006, Table S4.3, Figure 4.2). In St Croix, fish numbers were similar among all three groups with two to three fish sighted on average (Table S4.3, Figure 4.2).

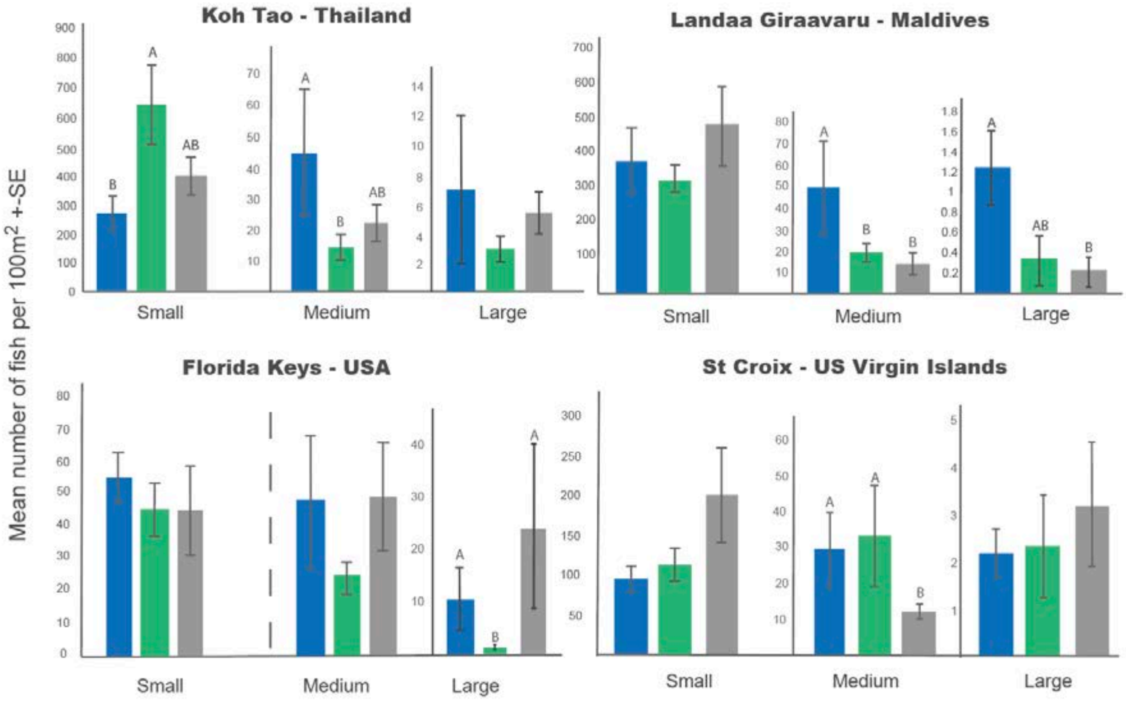


Figure 4.2 Mean number of fish observed per $100m^2$ transect (±SE) at all four locations in unrestored (blue), restored (green), and reference control sites (grey) in the three following size classes: small (<10 cm), medium (10 to 20cm), large (>20cm). Letters represent significantly similar or different pairs of sites from Tukeys' pairwise comparisons (Table S4.3). n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

4.3.3 Fish community composition

I expected to see differences in assemblage structure among the three treatments at each location. In particular, if the restoration was having a positive effect, then I expected that the fish assemblage structure at restored reefs would be intermediate to unrestored and control reference reefs. I hypothesised that restoration locations where benthic complexity was most improved would have stronger fish assemblage responses (i.e., between restored, unrestored and control reference groups). In contrast differences in coral cover, coral diversity and any species-specific patterns among reef types would not have consistent effects on fish assemblage differences. These effects were evaluated on the differences in fish familial level dominance among restored, unrestored and control reference sites, and on the differences in familial composition within each size class.

Differences in the composition of fish communities among restoration treatments only occurred in Koh Tao and not at the other three locations (Figure 4.3). In Koh Tao, reference control sites had a significantly different composition of fish families to unrestored sites (ADONIS F=0.16, p=0.014, Table S4.4). The fish community composition at restored sites appeared to sit in between unrestored and control reference sites. Hard coral cover and structural complexity had the strongest influence on differences among treatments (ADONIS, hard coral cover, F=2.73, p=0.018; structural complexity F=3.23, p=0.014, Table S4.5) with typically higher coral cover and/or complexity at the reference and restored sites compared to unrestored sites (Figure 4.3). There was also a significant site effect on the composition of the fish community in Koh Tao (ADONIS, F=2.11, p=0.002, Table S4.6).

At Landaa Giraavaru, the Florida Keys, and St Croix, the fish community compositions did not differ significantly among treatments (Figure 4.3, Table S4.4). That is, familial level characteristics at each location were similar among the restored, unrestored and reference control sites resulting in minimal distinction of fish communities. However, assemblage characteristics did differ among sites at all four locations (ADONIS, Table S4.6), suggesting that the location of sites had an impact on the fish assemblage structures.

Fish community assemblages were variably correlated to benthic attributes at each of these three locations (Figure 4.3, Table S4.5). In Landaa Giraavaru, neither hard coral cover nor structural complexity significantly influenced the composition of the fish communities among treatments (ADONIS, hard coral cover F=0.97, p=0.44 NS; structural complexity F=1.62, p=0.122 NS, Table S4.5). But, the assemblage was significantly influenced by *Acropora* density (ADONIS, F=6.01, p=0,001, Table S4.5) which was 1.5 times higher at restored sites than unrestored sites (Chapter 3, Figure 3.10), and conversely by coral generic richness (ADONIS, F=2.35, p=0.41, Table S4.5) which was 1.5 times lower at restored than unrestored sites (Chapter 3, Figure 3.7). In the Florida Keys, only structural complexity influenced the composition of the fish community (ADONIS, F=2.61, p=0.033, Table S4.5), with 1.5 times higher complexity at restored compared to unrestored sites (Chapter 3, Figure 3.4). In St Croix, the composition of the fish community was influenced by all benthic variables, except for structural complexity (ADONIS, hard coral cover F=7.13, p=0.001; structural complexity F=1.23, p=0.28; *Acroporids* F=3.14, p=0.022; gorgonians F=9.17, p=0.001; coral diversity F=6.13, p=0.02, Table S4.5). There, restored sites had higher structural complexity, coral diversity, and *Acropora* density than unrestored sites (Chapter 3, Figure 3.4, 3.7, 3.10).

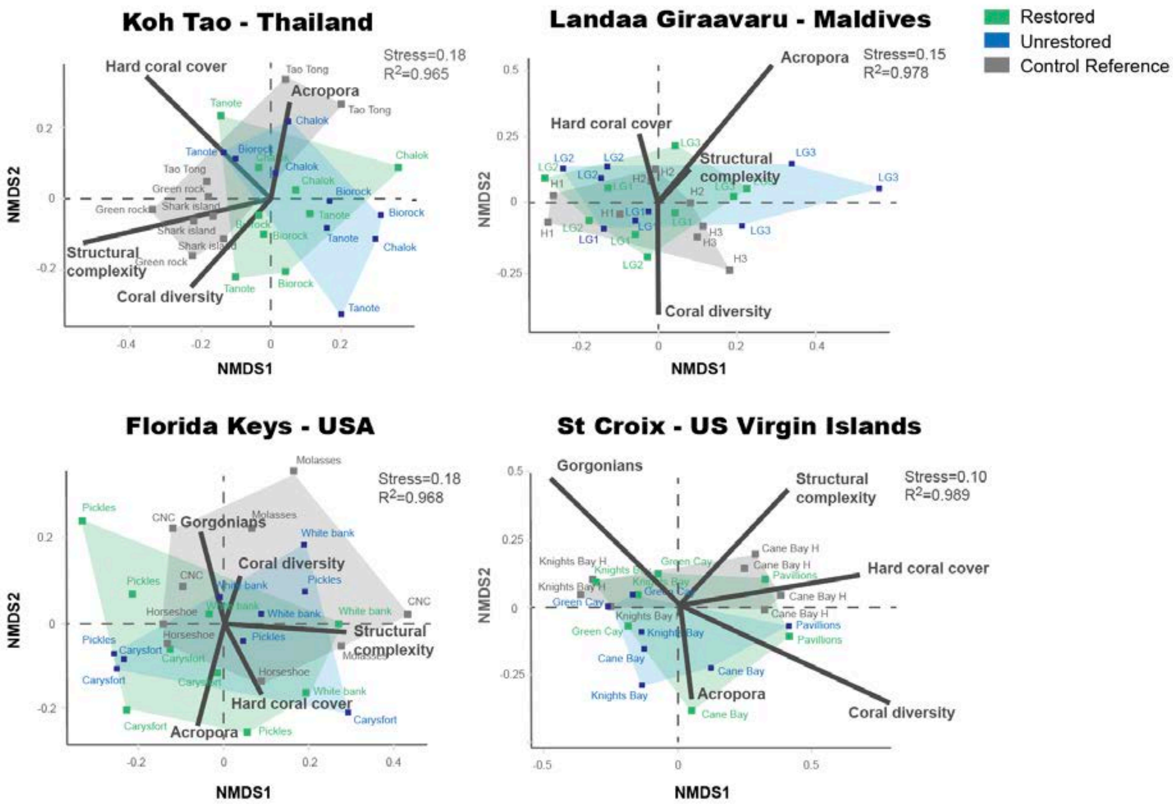


Figure 4.3 Effect of coral restoration treatments on composition of reef fish (by family level) at four geographic locations, as represented by non-metric multidimensional scaling. Polygons represent fish composition in each treatment, where green polygons encompass restored sites, blue polygons encompass unrestored sites, and grey polygons encompass control reference sites. Coloured shading reflects the location of the respective set of sites in non-metric multi-dimensional scaling space. Vector lines represent the influence of benthic attributes on the fish community composition

4.3.4 Fish community composition by size

Small fish community composition

Substantive treatment differences in the familial dominance of fish assemblages in the small size class only occurred at Koh Tao and not at the three other locations (ADONIS, Koh Tao F=2.40, p=0.01, Table S4.7). In Koh Tao, these differences were driven by damselfish which were twice as abundant at restored compared to unrestored sites (Figure 4.4). This family contributed to 80% of the differences found among the three treatment assemblages (SIMPER). Damselfishes also had the strongest contribution to assemblage differences in St Croix, contributing 70% (SIMPER). There, although the treatment differences were not significant (ADONIS, F=1.008, p=0.1, Table S4.7), there were three times as many damselfishes at control reference sites than in restored and unrestored sites (Figure 4.4). Wrasses contributed to minor differences in the small fish community among treatments in both the Florida Keys and St Croix (respectively 25% and 20%, SIMPER). Surgeonfishes and triggerfishes contributed to differences in the small fish community among treatments in Landaa Giraavaru (respectively 18% and 12%, SIMPER) (Figure 4.4).

Medium fish community composition

The fish community composition of medium sized fishes did not vary significantly among restoration treatments at any of the four locations (ADONIS, Table S4.7, Figure 4.4). In Koh Tao, medium sized cardinalfishes and damselfishes had a cumulative contribution of over 75% and 45% respectively (SIMPER) in driving differences in fish community composition with about 10 times more medium cardinalfishes and damselfishes observed at unrestored sites compared to restored and control reference sites (Figure 4.4). In St Croix, medium surgeonfishes had a cumulative contribution of over 35% (SIMPER) in explaining differences in the fish community composition between unrestored sites and restored and control reference sites with twice as many surgeonfishes in unrestored sites than in restored and control reference sites. Medium damselfishes and grunts contributed to most differences between restored and control reference sites (SIMPER 24% and 22% respectively), with more than twice as many of both fish from these families at restored sites compared to control reference sites (Figure 4.4). In Landaa Giraavaru, medium breams and fusiliers were only present in unrestored sites and thus had high cumulative contributions to differences among treatments (SIMPER, 40% and 70% respectively) (Figure 4.4). In the Florida Keys, the medium fish community composition at restored sites was characterised by two-times less grunts compared to unrestored and control reference sites, with grunts contributing to 50% of differences among treatments (SIMPER). Control reference sites also had twice as many medium damselfishes as unrestored and restored sites, giving damselfishes a cumulative contribution of 60% (SIMPER) in explaining differences among treatments (Figure 4.4).

Large fish community composition

The fish community composition of large fishes only varied significantly among restoration treatments in the Florida Keys (ADONIS, Florida Keys, F=2.44, p=0.01, Table S4.7, figure 4.4). There, large grunts had a cumulative contribution of over 40% in explaining the difference among treatments (SIMPER), being twice as abundant at control reference sites than unrestored sites and absent from restored sites. Large parrotfishes were also twice as abundant at control reference sites compared to both restored and unrestored sites (Figure 4.4) In Koh Tao, large fusiliers were only present at unrestored sites, cumulatively contributing to 77% (SIMPER) of the difference in fish community composition of large fishes between unrestored and restored sites, and 55% (SIMPER) of the difference in fish community composition of large fishes between unrestored and reference control sites. Large groupers were also twice as abundant at unrestored sites compared to restored and reference control sites, while large rabbitfishes were twice as abundant at reference control sites than in restored and unrestored sites (Figure 4.4). In Landaa Giraavaru, large parrotfishes were absent from restored sites. Large parrotfishes had a cumulative contribution of 22% (SIMPER) in explaining differences in large fish community composition between unrestored and restored sites, and of 30% (SIMPER) in explaining differences in large fish community composition between unrestored and reference control sites (Figure 4.4). In St Croix, there were twice as many large grunts at unrestored than restored and reference control sites. Grunts had a cumulative contribution of 74% (SIMPER) in explaining differences in large fish community composition between unrestored and restored sites, and of 75% (SIMPER) in explaining differences in large fish community composition between unrestored and reference control sites. Restored sites had twice as many large trumpet fishes than unrestored and reference control sites, while reference control sites had twice as many large triggerfishes than restored and unrestored sites (Figure 4.4).

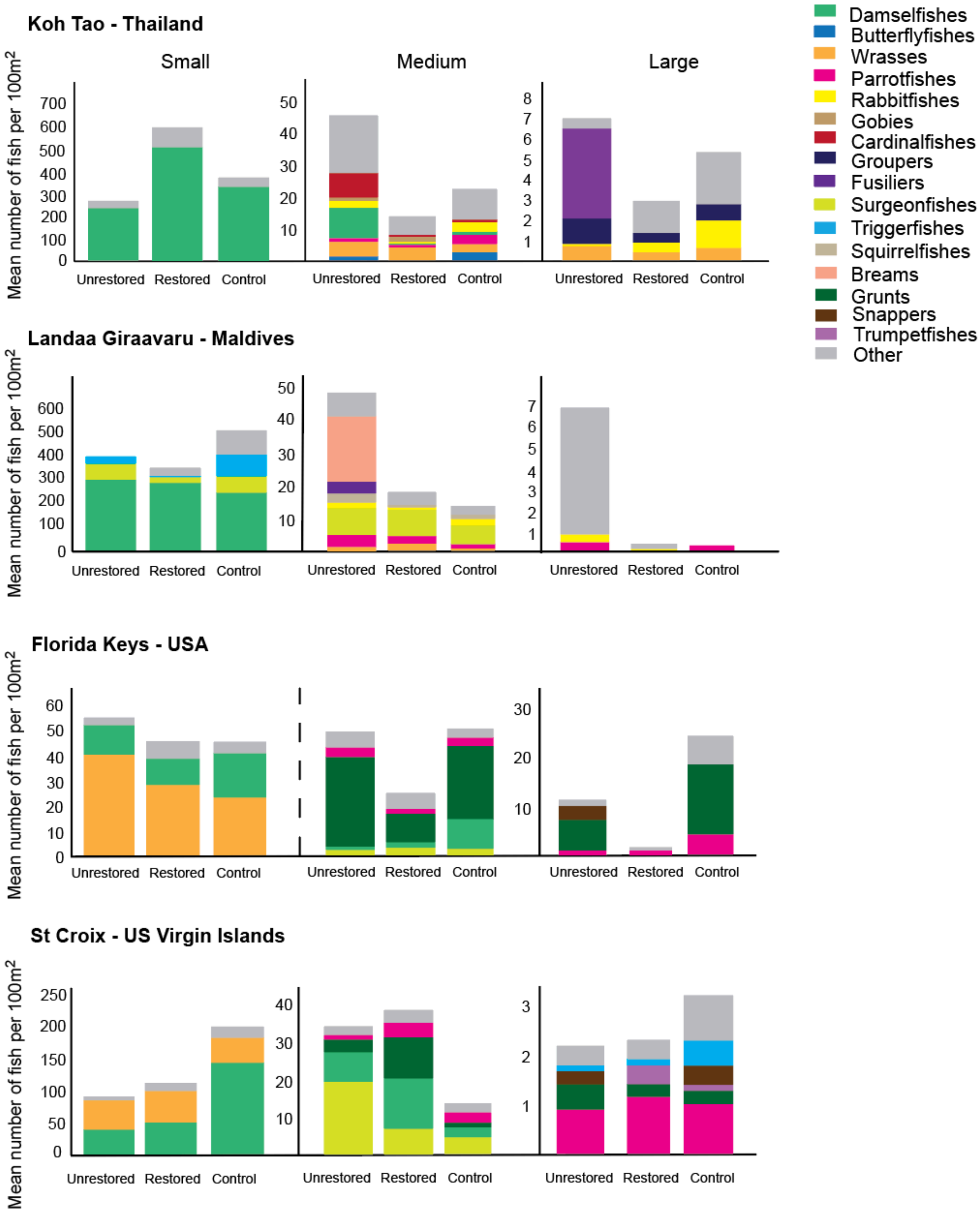


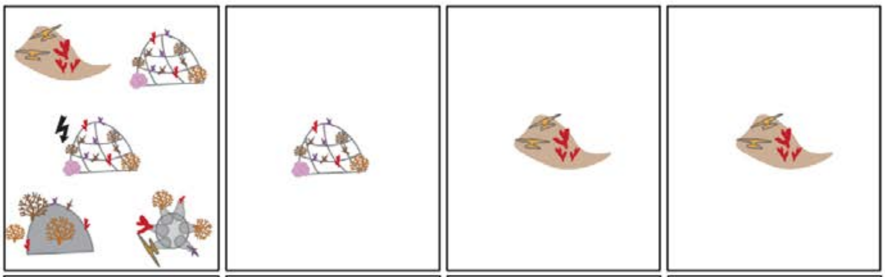
Figure 4.4 Mean number of most influential fish (post-simper analysis) per 100m^2 transect at all four locations in unrestored, restored, and reference control sites in the 3 following size classes: small (< 10 cm), medium (10 to 20cm), large (>20cm). n=9 transects per treatment in Koh Tao, Landaa Giraavaru and the Florida Keys; In St Croix, n= 8 transects for unrestored and restored treatments, n=6 transects for the control reference treatment

4.3.5 Summative effects of coral restoration on fish assemblages

Across all four locations, the effect of positive changes in benthic variables on fish abundance, due to restoration work, was highly variable. Differences at restored compared to unrestored sites, as indicated by ratios of difference (Table 4.1), while strong for hard coral cover and structural complexity, were not mirrored in the total fish abundance variables for all locations. The highest ratio of increased total fish abundance was in Koh Tao and linked to the highest ratio of increase in structural complexity (Table 4.1). Yet, the significant increases in both hard coral cover and structural complexity in Landaa Giraavaru and the Florida Keys only resulted in non-significant positive increases in fish abundance at the former, and a slight decline (also non-significant) in the latter (Table 4.1).

The linkage between benthic changes and fish assemblage changes within size classes also varied by location and/or restoration design. The only significant increase in fish abundance that matched strong and significant benthos changes was among small fish in Koh Tao where an array of artificial and direct transplant methods were used (Table 4.1). In contrast, the differential in abundance of medium fish was lowest in restored sites (significantly so), where artificial structures were used (Koh Tao and Landaa Giraavaru) and slightly higher where direct transplantation was used (Florida Keys and St Croix, Table 4.1). There was no clear effect of designs and benthic shifts on any large fish communities with neutral or negative fish responses mismatched to positive benthic shifts.

Table 4.1 Summary table comparing benthic and fish indicators surveyed at the four study locations with different restoration designs. Numerical values represent ratios of each metric at restored compared to unrestored sites. Coloured boxes represent the significance of the difference between restored and unrestored sites. Green denotes significant positive ratios, red denotes significant negative ratios; blue denotes non-significant differences



		Koh Tao-Thailand	Landaa Giraavaru-Maldives	Florida Keys-USA	St Croix-US Virgin Islands
Hard coral cover		+3.38*	+3.11*	+5.25*	+1.50
Structural complexity		+2.23*	+2.13*	+1.29*	+1.61*
Total fish abundance		+2.07	-0.80	-0.62	+1.19
Fish abundance by size	Small	+2.40*	-0.80	-0.82	+1.22
	Medium	-0.32*	-0.37*	-0.51	+1.13
	Large	-0.42	-0.27	-0.14*	+1.06

4.4 Discussion

This study illustrates an overall limited effect of coral restoration on the fish population assemblages at all four restoration programs despite substantial restoration-driven changes on the benthic community (Chapter 3). Contrary to my initial hypotheses, I did not detect any consistent effect of coral restoration on total fish abundance, or on the composition of fish communities. Instead, fish responses to restoration were location and size-specific. The magnitude of the fishes' responses to coral restoration also varied across the different types of coral restoration design, with the strongest positive response occurring where a variety of artificial structures were used. Increases in hard coral and structural complexity at restored sites were insufficient to predict the response of fish communities to restoration. Results from this chapter thus suggest that fish responses to coral restoration are more complex than previously assumed, and that careful considerations of location-specific diversity, abundance, and distribution dynamics are necessary.

4.4.1 Limited influence of hard coral cover and structural complexity on fishes' responses to coral restoration efforts

The significant increases in hard coral cover and/or structural complexity in response to coral restoration observed at all four locations (Chapter 3, section 3.3) did not necessarily result in positive responses of the fish communities. These results contradict my initial hypothesis since both high coral cover and structural complexity have been shown to be critical driving forces of healthy reef fish community assemblages (e.g. Carpenter 1992, Roberts & Ormond 1987, Gratwicke & Speight 2005). One possible explanation is that while significant, the rates of change in both metrics remained too weak to trigger long-term, lasting changes in the total number of fish, and the composition of the fish community. In the Florida Keys and St Croix, structural complexity remained average (around 2.5/5) at restored sites, while in Landaa Giraavaru, even unrestored reef sites had above average structural complexity (Chapter 3, section 3.3). A previous study in Indonesia by Ferse (2008) reported that fish abundance only increased in restoration plots where coral cover was initially very low (below 5%), highlighting the importance of the condition of the ambient reef in measuring fish response to coral restoration. Moreover, the previous studies that have documented a positive response of fish communities to coral transplantation usually have coral transplanted on either concrete structures (Edwards & Clark 1993, Carr & Hixon 1997, Cabaitan et al. 2008, Fadli et al. 2012), and/or in high-density plots (Cabaitan et al. 2008, Dela Cruz et al. 2014, Huntington et al. 2017). In these cases, there were substantial increases of both hard coral cover and three-dimensional complexity in the restored sites. In my study, even where the rates of change in both metrics where high (i.e., more than doubled in Koh Tao), the response of the fish community was limited to an increase in the abundance of small damselfishes. It is thus likely that factors other than hard coral cover and structural complexity need to be considered to predict changes in fish abundance and fish community composition in response to coral restoration.

Specifically, the location of the restored sites likely plays an important role in the potential for fish colonisation, either by settlement or post-settlement processes. Additionally, increased fish recruitment into restored areas necessitates the presence of healthy fish populations in the area. Among my study locations, the existence of healthy reef fish communities and the proximity of these to restored sites was quite varied. Post-settlement fish colonisation into the restored sites may have been hindered by isolation from the healthy reef areas that were kilometres away, particularly in Koh Tao and St Croix. There, the reference control sites have abundant fish assemblages but are very distant from the restored and unrestored sites (scale of kilometres). However, where treatment and control sites were closer together, such as in Landaa Giraavaru, I still did not detect a response in fish abundance to the coral restoration efforts. There, it is possible that the presence of territorial farming damselfishes in the restored sites (pers. obs.) may have prevented the colonisation of other fish species (Low 1971, Kock et al. 2016). Finally, in locations like the Florida Keys, where there is limited evidence of a resident healthy fish population anywhere in the area, paucity of source recruits likely drives the overall lack of restoration effect. My results partially corroborate those of Huntington et al. (2017) who only detected positive responses of fish to restoration where there was an established, robust fish community.

Fish colonisation is also influenced by species specific behaviour (Shulman 1985) and thus is unlikely to be uniform across different fish species, or functional groups (i.e., corallivorous, herbivorous, piscivorous). However, I was not able to test assumptions linked to species- and functional group-specific behaviours due to the low taxonomic resolution of the fish surveys.

4.4.2 The responses of fish communities to restoration was size-specific

Fish assemblages of different size classes responded variably to the restoration efforts at all four restoration locations. The abundance of small fish was increased at the restored sites in Koh Tao, with small fish assemblages there dominated by small damselfishes. This guild is typically associated with high complexity and coral cover in the Indo-Pacific (Holbrook et al. 2000, Noonan et al. 2012), and their increased abundance at the restored sites in Koh-Tao is thus likely a direct consequence of the restoration efforts. The limited increase in the abundance of small fish at the other three locations could be explained by a disconnect between the timing of my surveys and the timing of fish recruitment to restored areas. Some studies report fast initial colonisation of fish around concrete structures (Edwards & Clark 1993, Yeemin et al. 2006, Shaish et al. 2010b), usually within the first four months. Yet, most existing studies typically survey the fish community for a year or less (Edwards & Clark 1993, Cabaitan et al. 2008, Shaish et al. 2010b). Here, all restored sites surveyed had corals transplanted between two and ten years, and I was thus unable to detect the immediate response of fish to coral restoration, but rather provide a long-term snapshot of the composition of the fish community at various restoration sites. It is possible that the composition of the fish community stabilised over time between restored and unrestored sites (i.e., spill over effect from restored to unrestored sites that are very close (max 60m away). Alternatively, it is also possible that the time-lag between coral transplantation at restored sites and positive effects on the reef fish community might be longer than expected. Detecting changes in the abundance and composition of the fish communities requires some key processes of ecological succession to occur. For example, small fish might recruit to small coral transplants initially, but it will take time for 1) juvenile fish to grow into medium and large fish, and 2) for other medium and large fish to come to prey on the smaller fish. The timing of this ecological succession process will also depend on the structure and type of corals present at the restoration sites, and whether or not it provides shelter for fish of different size categories.

The response of medium and large fish communities to restoration was either inconsequential or negative with typically less medium and large fish at the restored compared to unrestored sites. These differences were largely driven by fish families that are not coral-obligates such as fusiliers in Koh Tao, bream in the Maldives, and grunts in the Caribbean (Carpenter 1988, Nelson 1994). Instead, these larger fish might be attracted to the restored areas to prey on smaller fish and tracking their response to the restoration efforts would require successive rather than snapshot surveys. The limited number of large fish observed might also be a consequence of my sampling design, with 20x5 metres belts being too narrow to accurately count fish larger than 20cm in total length (Samoilys & Carlos 2000, Kulbicki et al. 2010).

4.4.3 Different restoration designs affected the magnitude of fish responses to restoration

The strongest responses of fish to restoration were observed at the location where structural complexity was most increased at the restored sites and where a range of different artificial structures were used in the design of the restoration efforts. Ultimately all the factors likely to influence fish colonisation to the restored sites are heavily dependent on the design of coral restoration from site-selection to the type of structure and coral used. I discuss some of these factors below.

Site selection

The structure of the fish assemblages varied among sites at all four locations suggesting that spatial characteristics other than the effect of the restoration efforts affect fish communities. Connectivity of the restored sites to healthy fish population (Huntington et al. 2017), and proximity to nursery areas (e.g. mangroves and/or seagrass) (Mumby et al. 2004, Dorenbosh et al. 2007) may improve the potential for fish recruitment at the restored sites. Other site-specific characteristics such as the depth of restored sites (e.g. Srinivasan et al. 2013), or high abundances of territorial damselfish at the restored sites (Ceccarelli et al. 2011) require more considerations that were beyond the scope of this study.

Type of structure

Here, the strongest response of fish was observed in Koh Tao where a mix of different artificial structures were used. Yet, the positive effects of these structures was primarily observed on small damselfishes. These structures thus appear limited in their capacity to attract other fish families (i.e., they do not mimic table corals or provide much overhanging shelter). Large fish require large shelters (Hixon & Beets 1989, Kerry & Bellwood 2012, 2016). Likewise, the stainless-steel domes used in Landaa Giraavaru might not provide enough variety of shelters to attract a wide array of fish species in abundance, especially since the unrestored reefs are already naturally complex (Chapter 3).

Where no artificial structure is used, the size and density of the coral fragments transplanted are likely to have the strongest effect on fish colonisation. Agudo-Adiani et al. (2016) have shown that the size and number of branches of *A. cervicornis* were positively related to fish abundance and diversity, with larger colonies sheltering diverse juvenile fish. Yet, while increased density and transplant size might be best to quickly increase hard coral cover and structural complexity, recent studies have shown that partial coral mortality is often greater in closely spaced restoration designs (i.e., *Acropora* sp. thickets) compared with discrete colonies (Huntington et al. 2017). More research is needed to define optimal density for Acroporids transplantation in the Caribbean that maximises the creation of habitat structure without compromising the health of the transplants.

Type of coral used

Maximising the genotypic, species, and phenotypic diversity of the corals used for transplantation is likely to increase the fish diversity of coral-obligated fish species. Diversity of coral growth forms also provide more complex habitat and diverse reef habitats are usually associated with more abundant and diverse fish communities (Williams 1991, Nahami & Nishihira 2003). Here, the strongest response of the fish assemblages was observed in Koh Tao, where there was the strongest increase in coral diversity for all four case studies (Chapter 3).

4.4.4 Limitations and further research

The low taxonomic resolution of the survey prevented me from drawing any conclusions on the impact of coral restoration on the functional diversity of the fish assemblages. I was thus unable to characterise key processes of reef resilience such as an increase in the biomass of herbivores. More details on the species identity of the fish colonising the restored plots is also necessary to better characterise the process of recruitment. For example, the size of fish is species-specific and would provide more information on whether small fish are juveniles, or just small-bodied fish. Belt transects could also be supplemented by other types of fish visual census to limit the potential bias of belt transects towards counts of small fish. Further studies could use video cameras (see Fox et al. 2005), or stationary point-counts. Finally, I only had a “snapshot” of the fish assemblages at one point in time for each of the sites, preventing me from capturing nuanced differences in terms of succession. Repeating censuses over time and across seasons would allow better characterisation of the succession process of the fish community assemblages at the restored sites, and limit the potential bias linked to random conditions on the day of the survey (e.g. poor visibility, current, etc.).

4.5 Conclusions

Responses of fish communities to coral restoration were highly location and size specific, and this study therefore confirms that fish responses to coral restoration are limited and complex. The positive effects of coral restoration on fish communities observed in Koh Tao on small fish provide evidence that fish community assemblages can respond to restoration-induced increases in hard coral cover and structural complexity, especially small damselfishes. Similar trends were observed in St Croix but less markedly so, probably due to the youth of the coral transplantation efforts, and the less substantial changes in hard coral cover and structural complexity between restored and unrestored sites. No effect of coral restoration was observed on the fish communities at either Landaa Giraavaru or the Florida Keys, despite marked increases in hard coral cover and structural complexity at both locations. The lack of response in Landaa Giraavaru may be attributed to the fact that local reefs there are naturally diverse and complex and sustain rich fish community assemblages. Lack of response in the Florida Keys may be attributed to the restoration design that limits overall increases in structural complexity, as well as the poor status of the resident fish community and site isolation.

In conclusion, I suggest that positive effects of coral restoration on fish communities may only be observed when i) reefs restored are highly degraded (i.e., initial coral cover and structural complexity is very low), and ii) when restoration efforts result in an increase of structural complexity above average (i.e., above a 2.5/5 complexity score), and iii) restored sites are well connected to nearby heathy reef fish populations. Coral restoration efforts aiming at increasing fish abundance and diversity on degraded reefs should strive to substantially increase both coral cover and structural complexity by maximising coral diversity, transplant corals in high-density plots, and use artificial transplantation substrata when possible.

CHAPTER 5

Characterising the effectiveness of coral restoration programs: socio-ecological perspectives of benefits and limitations

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5.1 Introduction

Ecological restoration is increasingly used around the globe to address the dramatic declines in the extent and function of many ecosystems due to rising anthropogenic and climate-change driven impacts (Young 2000, Aronson & Alexander 2013, Perring et al. 2015). In a sense, the rise of ecological restoration in the last 60 years represents a shift in the history of humanity's relationship with nature from intensive resource exploitation to resource conservation. This paradigm shift may be driven by a cultural norm and social awareness about the loss of species and habitats due to resource exploitation, as well as the recognition that nature is providing humanity with many "free" ecosystem services (Millennium Ecosystem Assessment (MEA) 2005). Yet, as we realise the importance of many ecosystem services for our own wellbeing and liveability, we are increasingly seeing these services diminish, and in some cases, vanish. In response, restoring ecosystems has recently become central to international conservation goals, especially in the face of climate change-related disturbances (Aronson & Alexander 2013, Suding et al. 2015). Rising atmospheric and oceanic temperatures, as well as increases in carbon dioxide have already been shown to seriously degrade ecosystem function globally. For example, global temperature increases associated with climate change have been shown to impact the timing of species' life events such as migration and reproductive cycles (e.g. Both et al. 2006), leading to mismatches, altering species demographics and survival (Walther et al. 2002).

Marine ecosystems and coral reefs are particularly affected by climate change (Hoegh-Goldberg & Bruno 2010). In just two years, the Great Barrier Reef in Australia has lost over 30% of its coral cover due to a mass coral bleaching event attributed to abnormally high sea surface temperatures (Hughes et al. 2017, 2018).

Similar catastrophic declines in coral cover are occurring globally (De'ath et al. 2012, Jackson et al. 2014, Eakin et al. 2016), and are exacerbated by other disturbances to reefs such as pollution, storms, crown-of-thorns starfish outbreaks, and coral diseases (Alvarez-Philip et al. 2009, De'ath et al. 2012, Wolff et al. 2018), leading to local and global changes in reef community functions and structures (Knowlton & Jackson 2008, Hughes et al. 2018). Such rapid changes are cause for great concern since coral reefs provide a wide range of valuable ecosystem services to local and global communities such as food security, commercial opportunities, coastal protection, and strong cultural values (Moberg & Folke 1999, MEA 2005). Accelerated climate-change and human pressures on coral reefs have led to a rapid rise in advocacy, and deployment of intervention strategies such as coral restoration are increasingly advocated to protect what reefs and associated reef-ecosystem functions we have left (Anthony et al. 2017, Darling & Cote 2018). Yet, in contrast to other ecosystems such as forests and wetlands, coral restoration is still in its infancy, and very much focused on small scale, short-term technicalities such as growth and survival characteristics of coral fragments post-transplantation (Chapter 2, section 2.2). While these are necessary for improving restoration designs, critical information as to whether coral restoration can successfully increase reef resilience is currently lacking.

Reef resilience is increasingly recognised as the main objective of reef ecosystem management (Maynard et al. 2015, 2017). Defined as the capacity of the reef ecosystem to resist and/or recover from acute and chronic disturbances (e.g. Mumby et al. 2007, Hughes et al. 2010), resilience typically encompasses ecological and social dimensions (Cumming et al. 2005, Folke 2006). The social dimension of resilience recognises humans as an integral part of ecosystem processes where the positive and negative impacts of degrading environments on social systems are considered as part of a social-ecological feedback loop (Glaser 2006, Marshall & Marshall 2007). Societies, especially those with low socio-ecological resilience (Marshall et al. 2013), also play a critical role in accelerating the declines of coral reefs worldwide with a range of anthropogenic pressures such as increased coastal development leading to increased sedimentation (McCulloch et al. 2003), coral diseases (Haapkylä et al. 2011), and decrease in water quality (Brodie et al. 2012). Increasingly, ecosystem management strategies are focused on socio-ecological systems rather than ecological systems alone, enabling better understanding of the socio-cultural, economic, and institutional forces driving changes (Folke 2006). The socio-ecological view of resilience thus integrates society's capacity to adapt and change as well as considering disturbances as opportunities for adaptive change (Berkes et al. 2003, Folke 2006).

Socio-ecological systems are complex, and the insights that are derived from studying them depend on the view they are studied from (i.e., eco-centric versus anthropocentric) (Glaser 2006). One framework, the "prism of sustainability" by Valentin & Spangenberg (2000), integrates four dimensions of socio-ecological systems: ecological (i.e., the biological system), social (i.e., people's involvement and support), economic (i.e., sustained funding and potential economic benefits), and governance (i.e., project management, institutional support and any pertinent laws or regulations). These four dimensions are increasingly integrated in the goals and definition of ecological restoration (Jellinek et al. 2013, Perring et al. 2015, Martin 2017), yet they are virtually absent from the coral restoration literature (Chapter 2, section 2.2). The strong ecological focus of coral restoration to date may be limiting the full suite of coral restoration learnings that could enhance coral restoration strategies and practices, and their resilience benefits.

The human dimension is particularly relevant to coral restoration since people are involved in all stages of the restoration process, from design to execution and monitoring. Involvement of volunteers and citizen scientists in restoration efforts has the potential to improve local and global stewardship of reef resources (Hungerford & Volk 1990, Elwood et al. 2017, Dean et al. 2018). Volunteers can also help to increase the capacity of coral restoration efforts both physically and financially, therefore widening the impact scale of restoration (Dhillion et al. 2004, Tulloch et al. 2013). Benefits of restoration are also ultimately for people in the form of sustained and/or increased ecosystem services (Martin 2017). Such benefits can only be understood by looking at coral restoration success from a socio-ecological perspective. Socio-cultural benefits of coral restoration are likely to include the spectrum of ecosystem services provided by coral reefs such as the provision of alternative livelihood opportunities, increased educational opportunities, building stewardship, maintenance of wellbeing, identity, place attachment, aesthetics and pride around resource condition (Kittinger et al. 2012, Frey & Berkes 2014, Hesley et al. 2017, Marshall et al. 2017). Economic considerations are also essential to better appreciate the full range of costs and benefits associated with coral restoration (Bayraktarov et al. 2015, Kittinger et al. 2016). Finally, governance considerations are central to the adaptive potential of coral restoration efforts. Restoring agency around the use and management of natural resources (i.e., empowering people in decision-making) is likely to be an important benefit of coral reef restoration, potentially increasing the capacity to better understand coral reef decline and its management (Bennet et al. 2016). Reef restoration managers not only need to understand if their coral out-plants are growing, but also the extent to which their work is meeting the public's expectations, as public support for the program is very important to securing long-term support (Bennet et al. 2016, Sterling et al. 2017). There is thus a pressing need to increase the understanding of the strengths and limitations of current coral restoration practices to enhance management and build best-practice frameworks to guide their use as socio-ecological conservation strategies.

The aim of this Chapter is to assess the perceptions of benefits and limitations associated with coral restoration efforts. More specifically, I aim to identify and document the potential benefits and limitations of contemporary coral restoration at a social-ecological scale to inform the current debate around the value of coral restoration, and the extent to which government and community investment might occur. I address these aims through the analysis of data from targeted key-informant interviews at four well-established coral restoration programs around the world.

5.2. Method

Face-to-face key-informant interviews were conducted at four well established coral restoration programs around the world: New Heaven Reef Conservation Program (Koh Tao, Thailand), Reefscapers (Landaa Giraavaru, Maldives), the Coral Restoration Foundation (Florida Keys, USA), and The Nature Conservancy Caribbean Program (St Croix, US Virgin Island) (Table S5.1, Appendix S5.1, Section 1). All four programs have been in operation for between 8 and 12 years and are recognised as successful in the coral restoration community. These four programs also vary in their specific objectives, methods of outreach and sources of funding

(Table S5.1, Appendix S5.1, Section 1), therefore providing a variety of contexts for this study. In order to identify the benefits and limitations of coral restoration globally, thirty respondents were interviewed at each location giving a total of 120 interviews. The selection of respondents followed a snowball sampling design after initial discussions with local program managers. Interviewees were stratified across a large range of stakeholders in terms of age, gender, roles (e.g. restoration program staff, dive industry personnel, members of the local community etc.) to increase variation and provide a breadth of perspectives (Table S5.2, Appendix S5.1, Section 1).

Interviews were conducted in English and typically lasted between 15 minutes and one hour. English was not a limiting factor, even in Koh Tao and Landaa Giraavaru since both locations are heavily reliant on English-speaking tourism. All interviews were audio-recorded and later transcribed. Data were analysed using NVivo (Version 11.4.2 (2081)), and the statistical software R (version 3.4.1).

5.2.1 Interview design, administration and analysis

A copy of the interview questionnaire is available in the supplementary materials (Appendix S5.1, Section 2). In brief, interview questions were organised into five sections: (1) demographics, (2) experience with coral reefs, (3) benefits and limitations of the coral restoration efforts, (4) financial aspects, and (5) overall opinions on the coral restoration program. In the first two sections, respondents were asked a series of closed questions about how long they had been in the given location, their experience as divers and snorkelers, as well as scalar questions in which they were asked to rate attributes of the local reefs in terms of beauty, coral and fish abundance and diversity. Responses were recorded on a scale of one to ten, where one was generally considered as “extremely bad” and ten was “extremely good”. For example, their perception of “Beauty” was assessed on a scale of one to ten, where one was “not at all beautiful” and ten was “the most beautiful reefs I have ever dived” (Q2.d.1, Appendix S5.1, Section 2). Prompts and flashcards were used to guide the respondents. For example, A linear scale running from 1-10 was presented to respondents on a laminated A4 sheet of paper to provide some visual reference to the respondent. The third section consisted of open-ended questions about both the benefits and limitations of coral restoration. These questions enabled respondents to speak freely about their perspectives and thus increase the breadth and depth of understanding. The last two sections included a mix of closed, open-ended, and scalar questions to guide the conversation towards more specific aspects of the restoration efforts such as financial aspects and long-term perspectives. The initial version of the survey was pilot tested with colleagues and willing program members for the purposes of ensuring that the survey questions were unambiguous, easy to understand, and easy enough to respond to.

To ensure anonymity, each respondent was given a code based on the location, as well as their role, and a number from 1 to 30 assigned in alphabetical order. Codes for locations were as follows: Koh Tao (KT), Landaa Giraavaru (LG), Florida Keys (FK), and St Croix (SC). Eight groups of respondents were identified based on their roles: program staff (PS), program interns (PI), program volunteers (PV), dive industry personnel (DI), conservation practitioners (CP), tourism industry (TI), fishermen (FI), and local community (LO). “Program staff” were people paid for their involvement in the restoration efforts; “program interns” were long-term volunteers, typically involved in the restoration efforts for two to three months; “program volunteers” were typically involved in the restoration efforts for one day to two weeks; “diving industry” were people involved in diving activities (e.g. dive shop owners, dive instructors, etc.) at the specific location; “conservation practitioners” were people involved more broadly in other conservation actions other than the specific coral restoration program, “tourism industry” were people involved in tourism activities (e.g. watersport industry); “fishermen” were people involved in commercial or recreational fishing activities, and “local community” included other people from the community living at the specific location.
These eight groups were then categorised as either “involved” for groups of people involved first-hand in the restoration efforts (program staff, program interns, program volunteers, and conservation practitioners), and “others” (diving industry, tourism industry, fishermen, and locals).

5.2.2 Identifying the benefits associated with coral reef restoration

Benefits of coral restoration were identified from responses to the question: “What do you think are the three best things about the coral restoration program?” The question used the term “best things” as a colloquial and more direct way to engage respondents to discuss the benefits of the programs. Answers to this question were coded into themes, sub-themes and categories (coding groups). A content analysis was performed to uncover the main themes from the responses. These themes were then checked with co-investigators to ensure that each were as independent as possible, and that all responses were accounted for. Further content analysis enabled sub-themes and categories to be identified. Coding was an iterative process, and co-investigators were repeatedly consulted to ensure homogenous interpretation and description of each coding group. The total number of sources (i.e., number of respondents), and references (i.e., numbers of citations) were also recorded for each coding group across all respondents. Finally, each coding group was analysed per groups of respondents, as well as across all four locations.

5.2.3 Identifying the limitations associated with coral reef restoration

Limitations of coral restoration were identified from responses to the question: “What do you think are the three greatest problems about the coral restoration program?”. Here, the term “greatest problems” was used as a colloquial way and more direct way to engage respondents in discussion about the limitations of the programs. Steps described above for iterative content analysis were repeated.

Coding groups, and groups of respondents were analysed as fixed factors. A variety of models were tested, including ones where explanatory variables were treated as having either additive or multiplicative effects, and where data were log-transformed. AICc model selection was used to select the model explaining the greatest variation in the data, i.e., the model having the lowest AICc score. Assumptions for model validity were checked through QQ plots and residual plots. When tests failed to meet the assumptions of a Gaussian distribution after log-transformation, non-parametric Kruskal-Wallis tests were applied. When applicable, post-hoc Tukey’s HSD tests were also applied to tease out differences among treatments and sites.

5.3 Results

A total of 120 participants responded to the interviews, with 116 participants responding to the “benefits” question, and 96 participants responding to the “limitations” question. Respondents who replied “*I don’t know*” were not included in the analysis.

For the benefits, five themes emerged from the initial content analysis: 1. Socio-cultural benefits, 2. Ecological benefits, 3. Project appreciation, 4. Positive experiences, and 5. Economic benefits (Figure 5.1; Table S5.3, Appendix S5.2). Six themes emerged for the limitations: 1. Technical limitations, 2. Management limitations, 3. Ecological limitations, 4. Restoration limitations, 5. Staff limitations, 6. Legislative limitations (Figure 5.1; Table S5.4, Appendix S5.2). Descriptions of each theme are given below (sections 5.3.1 and 5.3.2).

A total of 29 sub-themes were identified as benefits, and 34 sub-themes as limitations of coral restoration efforts across the different themes (Figure 5.1; Table S5.3, Table S5.4, Appendix S5.2). The most frequently mentioned sub-theme describing benefits was ‘ecosystem function’ under the theme ‘ecological benefits’, while the most mentioned sub-theme for limitations was ‘lack of capacity’ under the theme ‘technical limitations’ (Figure 5.1). The least mentioned benefits of coral restoration were ‘food security’, ‘legislative support’, and ‘legacy’. The least mentioned sub-themes for the limitations were the ‘lack of regulations and enforcement’, ‘inadequate government funding’, ‘over-ambitious’, and ‘limited site-accessibility’ (Figure 5.1).

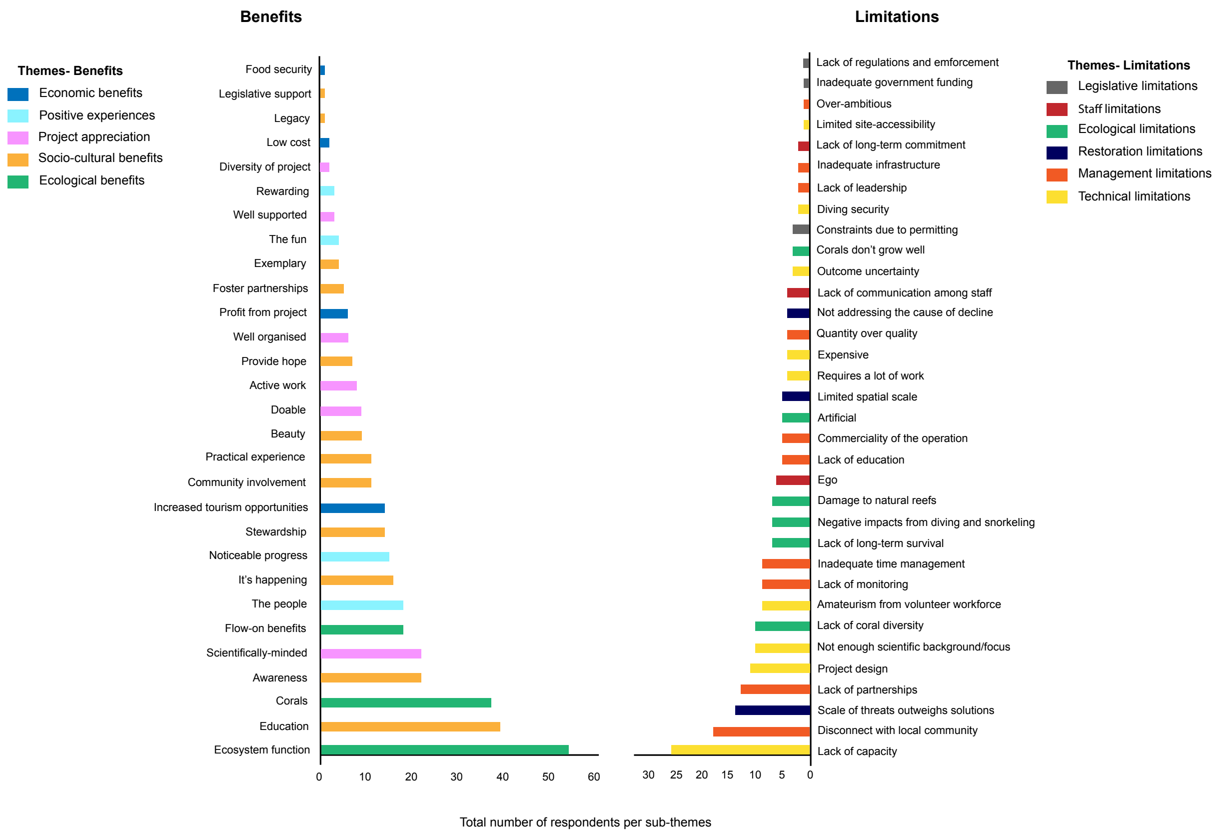


Figure 5.1 Total number of respondents mentioning each sub-theme for both benefits (n=116 respondents) and limitations (n=96 respondents) of coral restoration efforts

5.3.1 Benefits

Among the five over-arching themes identified for benefits of coral restoration, the themes ‘socio-cultural benefits’ and ‘ecological benefits’ were significantly more frequently mentioned than the other themes (see p-values in Table 5.1). ‘Socio-cultural benefits’ was the most frequently mentioned theme, with 72.4% (n=84 sources) of the respondents mentioning a total of 183 items that were grouped under that category (Table S5.3, Appendix S5.2), followed by ‘ecological benefits’ (68.9% of the respondents, n=80 sources), ‘project appreciation’ (31.9% of the respondents, n= 37 sources), ‘positive experience’ (30.2% of the respondents, n=35 sources) and ‘economic benefits’ (18.9% of the respondents, n=22 sources).

Table 5.1 Tukey's contrasts multiple comparisons with adjusted p-values for the proportion of responses per theme of benefits. * indicates significance

Comparison	p. adjusted
Ecological benefits – Project appreciation	0.0014*
Economic benefits – Project appreciation	0.9228
Positive experience – Project appreciation	0.9997
Socio-cultural benefits – Project appreciation	0.0028*
Economic benefits – Ecological benefits	<0.001*
Positive experience– Ecological benefits	<0.001*
Socio-cultural benefits – Ecological benefits	0.9998
Positive experience – Economic benefits	0.9684
Socio-cultural benefits – Economic benefits	<0.001*
Socio-cultural benefits – Positive experience	0.0013*

5.3.1.1 Socio-cultural benefits

The theme 'socio-cultural benefits' referred to responses attached to the human dimension of the restoration efforts and benefits at the scale of the local community. Responses under the theme 'socio-cultural benefits' were provided by 72.4% of the respondents at all four locations (Table S5.3, Appendix S5.2). Twelve sub-themes were identified ranging from 'education' (n=32 sources), to 'community involvement' (n=11 sources), and 'beauty' (n=9 sources) illustrating the broad nature of potential socio-cultural benefits linked to coral restoration efforts. The sub-theme 'education' was also the second most mentioned benefit of coral restoration (Figure 5.1). 'Education' was linked to increased awareness of coral reefs and associated threats and solutions. For example, one respondent suggested:

"*It's brought a lot of public awareness. People are a lot more aware of the problems going on out there when we try to talk about what we're trying to do to fix it*."
FK12CP,

Another respondent described possible solutions:

"*The hands-on part as well. You feel like you're actually out there, helping out, making a difference*" KT12PV, and encouraged stewardship:

"*Make people learn and feel like they protect the reef*" KT02LO.

The sub-theme 'community involvement' described hands-on, practical experience with the idea that it is not just about getting people involved in coral restoration, but also about giving them practical involvement:

"*It's good to have guests involved that way and have them do it.*" LG05DI

The sub-theme 'It's happening' included responses from 16 sources across all four locations. Respondents strongly valued the mere fact that coral restoration efforts were in place (i.e. that something was being done to address the threats to the coral reef):

"*The fact that there is an effort going in to actually try and restore the reef, which I think is very important*" LG04PS.

This concept was also linked to the sub-themes 'provide hope' (n=7 sources) and 'legacy' (n=1 source) that reflect that not all is lost, and that coral restoration is bringing some optimism for the future of coral reefs:

"*It's providing a hopeful message about the future that while we are being destructive in certain ways, we also have it in our own hands to be able to fix things for the future*." FK03PI.

5.3.1.2 Ecological benefits

The theme 'ecological benefits' referred to responses attached to the reef dimension of the restoration efforts. Responses under the theme 'ecological benefits' were broadly categorised in three sub-themes: 'ecosystem function' (n=54 sources), 'corals' (n=37 sources), and 'flow-on benefits' (n=18 sources) (Table S5.3, Appendix S5.2). 'flow on benefits' referred to projects or actions that emanate from the restoration program and convey further benefits for the reef ecosystem. Participants thus recognised ecological benefits at various scales with flow-on benefits from the scale of the corals used for restoration:

"*Bringing back Acropora to reefs that no longer have it*" FK12CP,

to the scale of the reef ecosystem:

"*It's going to attract more fish life, diversity, it's going to help in the health in general, and help the corals grow and diversify*." FK24DI,

and to the scale of ecosystem services (e.g. coastal protection):

"*We have a lot of erosion and you know it helps out in this way*" LG12TI.

The sub-theme 'ecosystem function' was the most mentioned benefit of coral restoration (Figure 5.1), reinforcing the idea that respondents recognise that coral restoration is not just about planting corals back onto the reef, but that the efforts have implications at the scale of the reef ecosystem.

5.3.1.3 Project appreciation

Responses coded under this theme referred to positive links with a coral restoration project, rather than benefits flowing from the coral restoration efforts. Participants highlighted both the importance given to the role of science as well as to the logistics of the restoration efforts. For example, the sub-theme 'scientifically minded' ranked fifth as the most mentioned benefit (n=22 sources, Figure 5.1). 'Science' (n=13 sources) was also mentioned as a way to improve existing methods:

"*We can give corals to other researchers to do research work that may inform restoration*" FK05CP,

and to legitimise the effort:

"*It's done by marine biologists- I believe what they are doing. They know where to collect the corals, they don't just go and break things off*" LG10TI.

Respondents also recognised the importance of logistics of the restoration operation with sub-themes like ‘doable’ (n=9 sources), ‘well-organised’ (n=6 sources), and ‘well-supported’ (n=3 sources) (Table S5.3, Appendix S5.2), highlighting the importance of good management:

“*They are organised, you know, it’s been easy for us to learn because it’s pretty simple how you go through about the day*.” FK29PI.

Participants also appreciated the feasibility of the restoration efforts:

“*It’s really easy. You might have the opinion that it’s complicated but it’s actually quite simple. It’s mostly underwater gardening*." KT09PS.

5.3.1.4 Positive experiences

Responses under the theme ‘positive experiences’ also related to the coral restoration programs rather than outcomes of the restoration effort. The sub-theme ‘people’ (n=18 sources) revealed that the people involved in the program played a major role in participants’ experiences. For example, respondents noted positives linked to dedication:

“*I get to be taught by such educated and passionate people. The staff here I’ve learned so much from and I’ve been really inspired by*” KT24PI,

As well as to the diversity of people involved:

“*Meeting so many people from all around. Everyone from different experiences and we all learn from one another*” KT26PS,

The sub-theme ‘rewarding’ (n=3 sources) was also related to the sub-theme ‘noticeable progress’ (n=15 sources):

"*I think just really satisfying to see the corals and see that you’re making a difference*." KT12PV

These sub-themes are also linked to socio-cultural benefits of providing hope through tangible progress:

"*There's a full circle story. You can tell that you can actually see the impact.*" SC12PS.

5.3.1.5 Economic benefits

The theme 'economic benefits" referred to positive economic revenues from the restoration effort. Economic benefits were the least mentioned benefits among all five themes. The low emphasis of potential economic revenues from the program (n=6 sources) suggests that economic profits are not the primary motivation of restoration practitioners. Yet, some participants recognised that bringing back corals on the reefs could benefit the local economy, especially for responses coded under 'increased tourism opportunities' (n=14 sources):

"*Bring back the coral life which will bring back the marine life which will bring back the tourists*" FK09TI.

5.3.1.6 Location and role specific differences in responses for benefits

Responses varied across the four different programs surveyed (Figure 5.2A) as well as across the roles of the respondents (Figure 5.2B, 5.2C). For example, while perceptions of socio-cultural benefits were consistently brought up by over 60% of total respondents at all four locations, they were most strongly acknowledged by people directly involved in the restoration efforts (Kruskal-Wallis, chi-squared=5.4, df1= p=0.02, Figure 5.2C). People involved in the restoration efforts also mentioned benefits under the themes 'positive experience', and 'project appreciation' significantly more often than the other groups (Kruskal-Wallis, positive experience: chi-squared=5.3, df1= p=0.02; project appreciation: chi-squared=5.4, df1= p=0.02, Figure 5.2C).

Ecological benefits were also recognised widely across all four locations, but different sub-themes were brought up depending on the type of programs. In St Croix and the Florida Keys, responses were mostly focused on species conservation

(Table S5.3, Appendix S5.2). On the other hand, the notion that restoration efforts create new reef habitat was only brought up in Koh Tao and Landaa Giraavaru (Table S5.3, Appendix S5.2), which are the only two sites to use artificial structures for restoration. In Koh Tao where restoration efforts are part of a wider conservation program, responses were also more focused on flow-on benefits and actions that reduce further damage to reef ecosystems. In Landaa Giraavaru, responses were more focused on coastal protection (Table S5.3, Appendix S5.2), which echoes the dire situation of the Maldives Archipelago which is composed of a low-lying island system that is seriously threatened by sea level rise.

Ecological benefits were mentioned by all types of groups of respondents with no significant difference between groups of people directly involved in the restoration efforts and others (Kruskal-Wallis, chi-squared=2.1, df1= p=0.14, Figure 5.2C), suggesting that coral restoration is perceived as having ecological benefits by all type of stakeholders, and further echoes the flow-on benefits of education through the local community. Responses within the theme ‘economic benefits’ were most prevalent in Landaa Giraavaru which was the most business-oriented program as part of a luxury resort hotel complex, but even there, they were limited to less than 50% of the respondents (Figure 5.2A). Responses under that theme also varied among groups of respondents, being most often mentioned by locals and the tourism industry, and least often brought up by program staff and conservation practitioners (Figure 5.2). Locals and tourism industry were also the groups that most mentioned ecological benefits indicating that these people not only believe in the ecological benefits of coral restoration but also believe that bringing corals back will benefit the local economy. There was also a lower emphasis on economic benefits by program staff and conservation practitioners (Figure 5.2B).

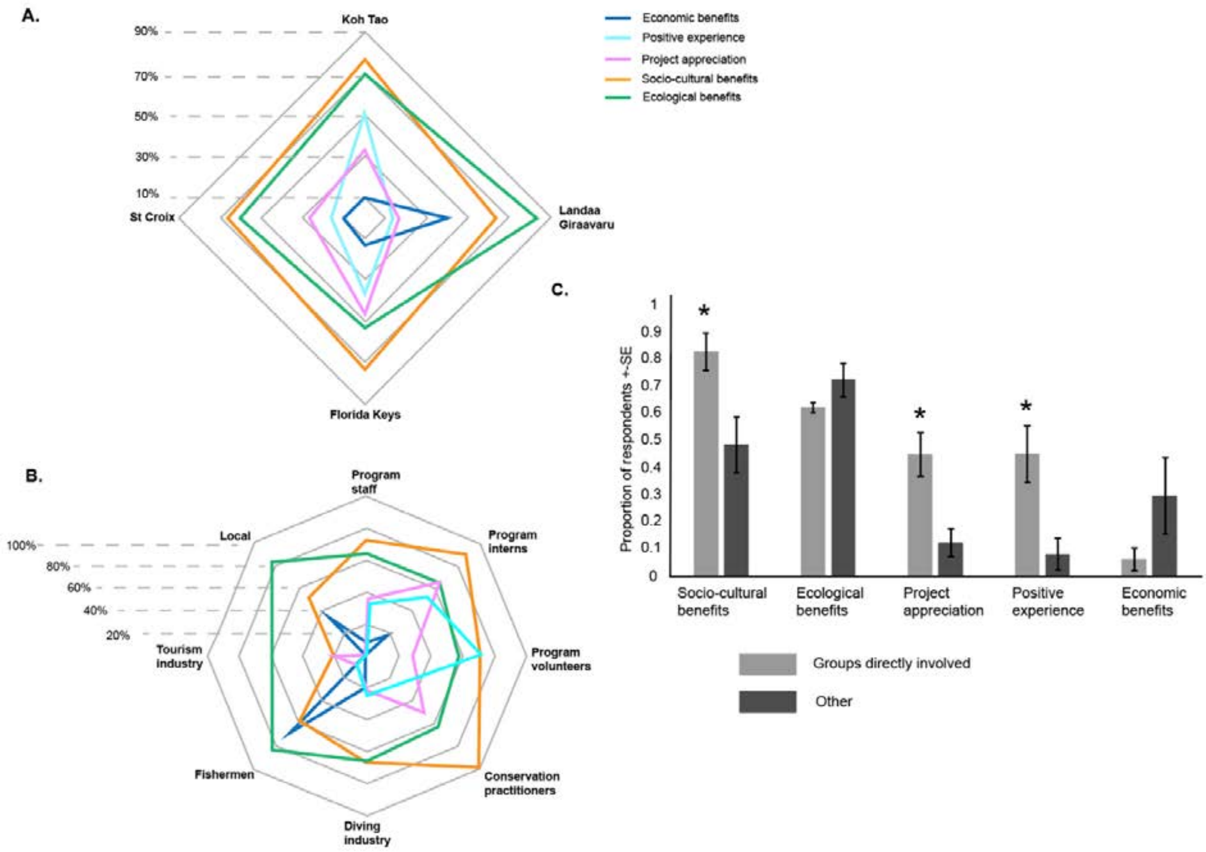


Figure 5.2 Variation in the proportion of responses for themes of benefits among all four locations (n=30 respondents per location) (A), group of stakeholders (B), and between groups of people involved directly in the efforts (n=60 respondents) and others (n=60 respondents) (C). * indicates significance. * indicates significance

5.3.2 Limitations

Among the six themes identified for the limitations of coral restoration, the themes ‘technical limitations’ and ‘management limitations’ were significantly more frequently mentioned than the other themes (see p-values in Table 5.2). The theme ‘technical limitations’ was the most common theme, mentioned by 58.3% of the respondents (n=56 sources), followed by ‘management limitations’ (42.7% of the respondents, n=42 sources), ‘ecological limitations’ (34.3% of the respondents, n=33 sources), ‘restoration limitation’ (19.8% of the respondents, n=19 sources), ‘staff limitations’ (11.4% of the respondents, n=11 sources), and ‘legislative limitations’ (5.2% of the respondents, n=5 sources) (Table S5.4, Appendix S5.2).

Table 5.2 Tukey's contrasts multiple comparisons with adjusted p-values for the proportion of responses per theme of limitations. * indicates significance

Comparison	p. adjusted
Governance – Ecological	0.0976
Management – Ecological	0.9962
Restoration – Ecological	0.5604
Staff – Ecological	0.0698
Technical – Ecological	0.0885
Management – Governance	0.0238*
Restoration – Governance	0.9358
Staff – Governance	1.0000
Technical – Governance	<0.001*
Restoration – Management	0.2577
Staff – Management	0.0157*
Technical – Management	0.2697
Staff – Restoration	0.8930
Technical- Restoration	<0.001*
Staff- Technical	<0.001*

5.3.2.1 Technical limitations

The theme 'technical limitations' referred to problems associated with the logistics of the restoration efforts. Several technical limitations were identified (Table S5.4, Appendix S5.2), and 'lack of capacity' (n=26 sources) was most talked about. For example, participants recognised the 'limited number of people involved' (n=15 sources) and the 'lack of funding' (n=14 sources) as major limitations:

"*We don't have enough people do all that we want to do of course*" FK18PS;
"*the funding is less than a level necessary to do the work properly*" SC01PS.

Participants also identified technical limitations linked to the programs' designs. For example, they raised issues linked to the 'material used for restoration' (n=5 sources) or with the 'location of transplantation' (n=3 sources):

"*I think one of the challenges with restoration at the moment is finding a material that is as strong as concrete but doesn't have the same environmental problems*" KT06PS);
"*Where the corals are actually being planted. I think they could do a better job with that.*" FK15PS.

In particular, some respondents criticised the lack of science behind the efforts (n=10 sources):

"*It would be nice if there was a little more science embedded in the methodology*" SC14PI.

Finally, an important technical limitation was linked to potential damage caused by untrained volunteer workforce (n=9 sources):

"*You go with [the] new student you see them struggling and that result in them doing a bit of a lousy job. The fragments might not be well secured and might fall off in the future*" KT07PI

5.3.2.2 Management limitations

The theme 'management limitations' referred to problems associated with decision-making in the execution of the restoration efforts. The most common limitation under that theme was linked to disconnects between the coral restoration efforts and the local community (n=18 sources). This disconnect was linked to 'lack of community awareness' of the program (n=7 sources):

"*I don't know that we are spread through the community very effectively.*" SC18PS.

Some respondents attributed the 'lack of community awareness' to a 'lack of communication with the public' (n=14 sources):

"There is very limited awareness of what they are doing, how they are doing it, everything*"* SC05DI.

Beyond members of the local community, respondents also criticised 'lack of partnerships' with other dive schools, other local or international conservation practitioners (n=13 sources):

"*The term partnership is too loose and there should be more of a coordinated effort if it's going to be a population enhancement project.*" FK12CP

Other management limitations were again linked to logistical limitations. For example, respondents criticised the time-management of volunteers, staff and interns, which was reinforced by criticisms of the limited time allocated to the monitoring of the restoration efforts:

"*Sometimes as an intern we tend to sit around and do nothing in the morning*" KT24PI;
"*Long-term and large-scale monitoring is probably our biggest issue. Because, it's just hard to understand the success.*" FK05CP

5.3.2.3 Ecological limitations

The theme 'ecological limitations' included responses that referred to unsatisfactory ecological outcomes from the restoration efforts. Several ecological limitations were raised by the participants with the 'lack of coral diversity' used in the restoration efforts raised as the most prevalent issue (n=10 sources, Table S5.4, Appendix S5.2):

"*We've only been focusing on Elkhorn and Staghorn corals whereas a healthy reef has a lot more diversity than that.*" SC18PS

Other limitations included poor health of the coral fragments used for restoration through 'limited long-term survival' post-transplantation (n=7 sources) or 'negative impacts from diving and snorkelling' at the restoration sites (n=7 sources):

"*A lot of fragments do die*." LG11PS;
"*A lot of the areas are well dived and that can actually affect the coral*." SC30FI

Finally, some participants mentioned potential 'damage to natural reef' through detrimental ecological effects of coral restoration on wild coral colonies (n= 7 sources):

"*It could actually damage the parent colonies from where they are getting the pieces of corals*". LG20LO

5.3.2.4 Restoration limitations

Responses under the theme 'restoration limitations' referred to limitations of coral restoration efforts as a reef management strategy (Table S5.4, Appendix S5.2). The main criticism was that the scale of the outside threats to the reef ecosystem outweighs the scale of solution (n=14 sources):

"*The problem is global and this is just one local solution. We put corals back on the reef, but it doesn't stop bleaching or tourism and people who would go break it.*" KT01PI.

Other criticisms included the limited spatial scale of the potential benefits of coral restoration (n= 5 sources), as well as the limited capacity of coral restoration to address the cause of reef declines (n=4 sources):

"*It's small scale- we help a few reefs on Koh Tao and it's not enough at all*" KT01PI;
"*It's like using duct tape over something that's broken. It doesn't fix the problem*" FK14PS.

5.3.2.5 Staff limitations

The theme 'staff limitations' was associated with internal issues within the restoration programs. These internal issues within the coral restoration groups were mostly driven by 'ego' and 'lack of communication among staff' members, and eventually affected the efficiency of the restoration work negatively:

"*There is too much turf battles and pride and less teamwork that there needs to be.*" FK28PS;
"*The information one person gets doesn't fan out to all the other people that need it. And you're always hunting people down to ask some questions.*" FK11PS.

5.3.2.6 Legislative limitations

The theme 'legislative limitations' referred to unsatisfactory support from local and national governments, and permit limitations. Legislative limitations were only raised by five participants across all four programs surveyed. 'Constraints due to permitting' was the most prevalent criticism (n=3 sources, Table S5.4, Appendix S5.2). For example, participants raised the issue that permit limitations often overruled common-sense in day-to-day operations of the restoration efforts, thereby negatively affecting logistics and efficiency:

"*Permitting requirements which are very specific, and tedious, and time consuming*" FK14PS

Other criticisms included inadequate funding support from the government (n=1 source), as well as lack of enforcement and regulations limiting their potential to scale-up their impacts beyond the localised restoration efforts (n=1 source):

"*The new regulations from last year - nothing is being enforced. We're working on trying to get things enforced, but it's difficult, it's not easy.*" KT09PS.

5.3.2.7 Location and role specific differences as limitations

Responses for limitations also varied by location (Figure 5.3A), and across different groups of respondents (Figure 5.3B, 5.3C). For example, 'technical limitations' were the most common limitations (over 50% of the respondents) brought up in both Koh Tao and the Florida Keys, while 'ecological limitations' were the most common limitations in Landaa Giraavaru (approximately 50%, Figure 5.3A). In St Croix however, 'technical' and 'management' limitations were both mentioned by about 40% of the respondents (Figure 5.3A). Other limitations were a lot more prevalent in certain locations such as "staff limitations" that were mentioned three times more often in the Florida Keys compared with any other locations (Figure 5.3A). 'Restoration' and 'legislative' limitations were also most mentioned in Koh Tao and the Florida Keys (Figure 5.3A), which are the two locations most threatened by overpopulation and tourism pressure creating issues with land-clearing, erosion, and rubbish disposal to name a few. The feeling of disconnect from the local community was less prevalent in the Maldives, and most prevalent in the US Virgin Islands

(Table S5.4, Appendix S5.2). The mention of ecological limitations also varied among locations, being two to three times more frequently mentioned in the Maldives than any other locations (Figure 5.3A; Table S5.4, Appendix S5.2).

In terms of differences among respondents, ‘technical limitations’ were mentioned significantly more often by groups of people involved in the restoration efforts than other groups (Kruskal Wallis, chi-squared=5.3, df=1, p=0.02; Figure 5.3C). Responses under the themes ‘management limitations’, and ‘staff limitations’ also tended to be more frequently mentioned by groups of people involved but the trend was non-significant (Kruskal Wallis, ‘management limitations’: chi-squared=2.08, df=1, p=0.14; ‘staff limitations’: chi-squared=0.98, df=1, p=0.32; Figure 5.3C). ‘Ecological limitations’ were the most mentioned limitation for the tourism industry, and it was also mentioned by over 40% of conservation practitioners (Figure 5.3B), indicating that these two groups of respondents are the wariest of potential negative ecological impacts of coral restoration impacts.
Less than 20% of the locals mentioned limitations of coral restoration, but of those who answered, all of them raised issues associated with ‘legislative limitations’. Finally, ‘restoration limitations’ were cited by respondents both directly involved in the restoration efforts and others (Kruskal Wallis, chi-squared=1.4, df=1, p=0.24; Figure 5.3C).

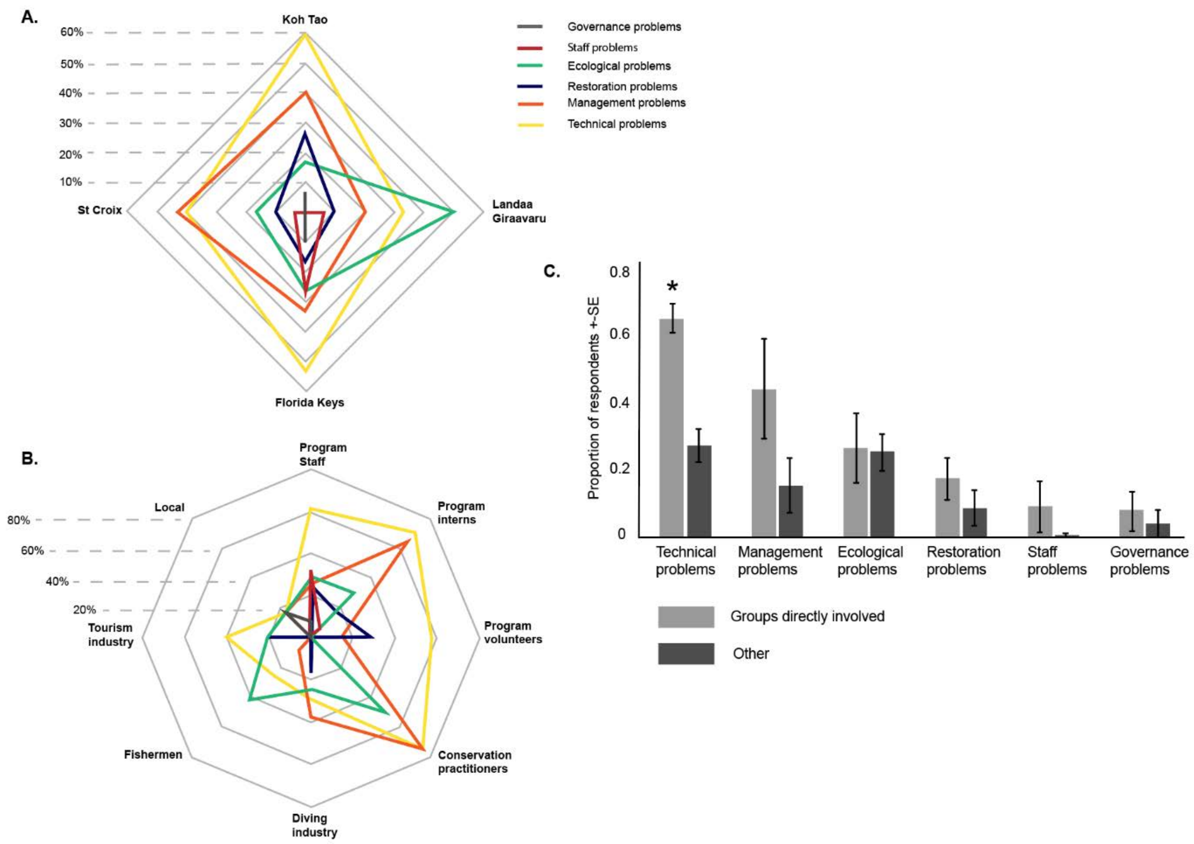


Figure 5.3 Variation in the proportion of responses for themes of limitations among all four locations (n=30 respondents per location) (A), group of stakeholders (B), and between groups of people involved directly in the efforts (n=60 respondents) and others (n=60 respondents) (C). * indicates significance

5.4. Discussion

This global study is the first to assess reef-users' and local community' perceptions of the benefits and limitations of coral restoration across different geographic locations. My results reveal that perceptions around coral reef restoration range far beyond ecological considerations and highlight the critical role that coral reef restoration plays in the lives of coastal communities, whilst acknowledging that there are important limitations to restoration efforts. By identifying how perceptions of key benefits and limitations vary across the four different programs, as well as among different types of respondents, I am able to develop insights into the importance of location-specific, as well as people-specific influences and characteristics. I discuss my most important findings.

5.4.1 Social outcomes out-weigh all other benefits

Socio-cultural benefits were the most frequently mentioned responses to the questions about the benefits of coral restoration. These results emphasise that the respondents' perspectives of benefits are very much geared towards socio-ecological outcomes rather than on ecological outcomes. These results also support recent claims that socio-cultural factors are central to goal-setting and assessing effectiveness of coral restoration efforts (Suding et al. 2015, Martin 2017). Many participants valued the restoration efforts for the mere fact that they were happening, reinforcing the importance of coral reefs in people's everyday lives, especially for cultural values and well-being (e.g. Kittinger et al. 2012, Cinner et al. 2015, Marshall et al 2017). Such results support the observation that people are aware of the vulnerability and declining status of reef ecosystems (Goldberg et al. 2016). Thus, not only do people care about the reefs for reasons beyond economic gains, but they are also concerned about the future of coral reefs. Participants also noted the importance of restoration efforts in providing hope for the future of coral reefs. This point is particularly important in view of recent movements such as #oceanoptimism (Knowlton 2017), which moves the narrative of coral reef science beyond "doom and gloom" to encourage agency through the stewardship of reef resources.

Involvement in coral restoration efforts fosters stewardship

Stewardship was one of the most frequently mentioned potential benefits of coral restoration. In particular, respondents highlighted the links between stewardship and education through the restoration efforts. These findings are in line with work by Hunterford & Volke's (1990) and Dean et al. (2018) who suggested that conservation education and stewardship are strongest when applied through practical experiences. Citizen participation in conservation activities also leads to greater community acceptance and faster implementation of management actions (Danielsen et al. 2010). These results also support the findings of Hesley et al. (2017) who found that the "hands-on" aspect of coral restoration promotes stewardship. However, while Hesley et al. (2017) did not find any negative ecological effect from using volunteer workforce, several respondents in this study mentioned trade-offs between education and the ecological outcomes of the restoration efforts due to the potential damage caused by the amateur, volunteer workforce.

These problems resonate with studies looking at the effectiveness of citizen science that show scientists' reluctance to trust public involvement in data collection (Golumbic et al. 2017). When applied to coral restoration, it appears that while practitioners value public participation as critical to engage the public, promote conservation and stewardship, they do not necessarily trust the public to transplant corals back onto the reef efficiently. In citizen science, Pocock et al. (2015) have described a trade-off between biological monitoring designs that are ideal for statistical analysis and designs that allow for public participation that increase the monitoring program goals. Here, the trade-off is between having the best planting design to maximise coral growth and having more hands to scale-up the restoration efforts. This trade-off issue was brought up by restoration staff whose definition of coral restoration success is to have many corals securely attached to the reef. Given the clear importance given to socio-cultural benefits of coral restoration in this study, I suggest that goals for coral restoration should more explicitly embrace socio-cultural objectives, in order for practitioners to realise the numerous benefits of public engagement in hands-on restoration activities (Danielsen et al. 2010, Kittinger et al. 2016). For example, a higher emphasis on proper training volunteers, as shown in Hesley et al. (2017), might help overcome the trade-off between scientific design and volunteer workforce capacity and efficiency.

Respondents value scientifically-driven projects

Many participants also highlighted the role of science as both a benefit and limitation to restoration. The criticism that restoration projects require a more robust scientific research basis for coral-planting efforts was very prevalent in the 'identifying limitations' responses. These results echo calls from the scientific community for the need to rapidly advance coral restoration ecology research (Rinkevich 2015). These responses also suggest that the science underpinning current restoration methodologies (e.g. Rinkevich 2005, Johnson et al.2011) is not necessarily used by coral restoration managers. In the responses to the benefit questions, science was linked to project appreciation, highlighting that participants valued robust scientific design for the restoration efforts. These responses also suggest that coral restoration projects can be used to enhance scientific understanding and capacity in non-research trained volunteers (Garbarino & Mason 2016).

5.4.2 Ecological outcomes surpass the coral-planting phase

Responses related to ecological benefits of coral restoration were more focused on benefits at the scale of the reef ecosystem (e.g. “increased diversity of marine life”, “coastline protection”) than that of the coral transplants *per se*. These results suggest that participants perceived that measuring ecological success of coral restoration efforts requires broader considerations than the typical short-term, coral transplant focus nature of the majority of coral restoration research studies to date (Chapter 2, section 2.2). Participants thus recognised ecological benefits at a much wider spatial scale than that of the restoration plots; this contrasts with the common criticism that the scale of impact of coral restoration is too limited to address current threats to coral reef ecosystems (e.g. Precht et al. 2005, Edwards & Gomez 2007). For example, many responses for ecological benefits related to reef ecosystem function such as increased diversity of marine life and improved habitat protection. Responses for ecological limitations also reflected larger scale ecological impacts of coral restoration with focuses on limited diversity of the coral assemblages and potential damage to natural reefs. Altogether, the diversity of potential ecological benefits and limitations brought up by the respondents confirms that studies investigating the effectiveness of coral restoration efforts need to account for a variety of indicators and follow principles of reef resilience (Chapter 2, section 2.3).

5.4.3 Local community involvement is important for the success of restoration

Low levels of local community involvement in the restoration efforts was one of the most important limitations brought up by the participants in this study. It was associated with both a lack of communication with the public and a lack of community awareness. These results suggest that the potential for education and stewardship potential through involvement in the coral restoration efforts is currently limited for local communities. The majority of program volunteers and interns were visiting tourists rather than locals. Yet, while engaging tourists is critical to spread awareness nationally and internationally, local communities are the ones who are most likely to directly benefit from the restoration actions. For example, Kittinger et al. (2016) have shown that members of the local community strongly benefited from improved well-being and increased cultural services from a reef restoration effort in Oahu, Hawaii, leading to increased community awareness of the threats to their reef-associated resources, and increased capacity for stewardship. The importance of including members of the local community in all stages of restoration efforts has also been put forward in numerous land- and watershed-based restoration projects (e.g. McGinnis et al. 1999, Dhillion et al. 2004), as a way to not only improve the direct benefits of the restoration to local stakeholders, but also to use locals' knowledge to more efficiently carry out the restoration efforts. Involving volunteers from the community thus appears to be vital for creating a sense of resource ownership and maximising the potential flow-on of socio-cultural benefits.

5.4.4 Good governance at multiple scales can help restoration efforts

The importance of governance for coral restoration effectiveness was recognised at different scales through the responses about both benefits and limitations. Scales of governance ranged from project management to legislative considerations and impacted participants' views of the projects' logistics as well as their appreciation and support.

At the lower end of the scale, participants emphasised the importance of the 'people factor' in responses about the benefits and limitations of coral restoration. Within the benefits, the people factor was mostly linked to positive experience which is an integral part of citizen science projects to increase participants' understanding (Garbarino & Mason 2016), and thus stewardship and long-term commitment. Participants need to enjoy the process. On the other hand, problems associated with people were mostly referred to as ego, and miscommunication problems among staff. While these may not necessarily impact the experience of the volunteers, it can impact the logistics and effectiveness of the restoration efforts. Issues with logistics were particularly common in the limitations results recorded in this study. Such results highlight that respondents valued the inner-workings of the restoration projects as an integral part of coral restoration effectiveness, as well as the importance of having a team of staff members that were dedicated, open to adaptive change, and able to commit long-term. Restoration programs should therefore strive to be well-organised and make the process as easy as possible, in order to maximise sustained project appreciation and support.

At the upper-end of the scale, respondents both valued and criticised legislative support. In the Caribbean especially, legislative shortcomings included permit limitations that hindered the progress of the restoration efforts as well as affected the day-to day logistics of the operations. While permits are important to hold restoration practitioners accountable for their actions and ensure that proper techniques and precautions are used, more discussions between restoration practitioners and legislative bodies might be necessary to adjust permit restrictions more efficiently with the day-to-day logistics, and new scientific discoveries. Legislative problems also included limited economic support from local and national governing bodies.

5.4.5 Secure funding for restoration success

Economic limitations were expressed as the lack of capacity for the restoration efforts and were thus one of the most important limitations brought up by the participants. While ecological restoration is increasingly recognised by international agencies as critical to safeguard ecosystem services in the face of climate change (e.g. Aronson & Alexander 2013, UN 2016, Martin 2017), funds distributed by governments are often short-term and small scale (Borgström et al. 2016). Among the four case-studies, the two Caribbean-based programs (Florida Keys and Us Virgin Islands) were initially partly funded through the American Recovery and Reinvestment Act (Johnson et al. 2011) but both have also had to source additional funding from the private sector (Table S5.1, Appendix S5.1 Section1). The other two programs (Maldives and Koh Tao) receive very limited funding support from their respective governments and rely on funding from interns and volunteers to sustain the restoration activities (Table S5.1, Appendix S5.1, Section 1). Altogether participants highlighted the limited economic capacity of the restoration programs as a constraint to their efficacy. Securing long-term funding thus appears to be an essential consideration to the planning of successful coral restoration programs. In particular, if the restoration goals are focused on socio-economic outcomes, then managers should intently consider funding targeting the training of volunteers and local community participants to both scuba-diving and restoration skills as part of their grant application.

5.4.6 Perceptions varied among locations and groups of respondents

Responses for both benefits and limitations varied among locations and group of respondents. Variations among locations highlight the context-specificity of people’s perception of coral restoration success. While the importance of context has been demonstrated for the ecological outcomes of coral restoration (Ladd et al. 2018), this study is the first to demonstrate context-specificity for socio-cultural outcomes.
The feeling of disconnect from the local community was one that particularly varied among the four locations, being less prevalent in the Maldives where locals are employed by the hotel through an apprenticeship program to work with the restoration program (Hein et al. 2018). It was most prevalent in the US Virgin Island where local islanders are disconnected from the ocean resources. Ecological limitations were also most frequently mentioned in the Maldives, which can probably be attributed to the mass coral bleaching event of 2016 that severely affected the Maldives at the time of the survey.
Responses also varied among different groups of respondents, especially between groups of people involved first-hand in the restoration programs and others. In particular, socio-cultural benefits were most often mentioned by groups of people involved first-hand suggesting highlighting that the objectives of coral restoration programs generally span beyond ecological outcomes alone (Chapter 2, section 2.2). The lower emphasis on economic benefits by program, staff and conservation practitioners also suggests that economic benefits are not the primary concern of people directly involved in the restoration programs (i.e., they are not doing this for money). On the other hand, other themes were also mentioned as frequently between people involved and others. That was true for responses within the theme “restoration limitations” for example, suggesting widespread uncertainty about the efficacy of coral restoration as a reef management strategy among stakeholders. Altogether, these differences among location and groups of respondents suggest that perceptions of restoration effectiveness are subjective, and therefore that the meaning of success is likely to be context-specific. These are important considerations for restoration managers, as managing for stakeholders’ perception of success is crucial to ensure long-term sustained support (Bennet et al. 2016, Sterling et al. 2017). Future research should investigate the variation in perceptions among

stakeholders more specifically. In Chapter 6, I assess in more details how perceptions vary among the different programs and stakeholder groups.

5.5 Conclusions

Respondents across all four locations provided a very rich range of responses to both benefits and limitations of coral restoration. These covered all four pillars of sustainability: ecological outcomes, social outcomes, governance outcomes, and economic outcomes (Valentin & Spagenberg 2000, Spagenberg 2004), suggesting that coral restoration is rooted in sustainability principles and needs to acknowledge and account for factors beyond ecological considerations (Ammar 2009, Suding et al. 2015, Chapter 2, section 2.3). While I identify several important limitations of coral reef restoration, particularly around amateur workforces, my results suggest that coral restoration can be used as a powerful conservation education tool to promote stewardship and enhance coral reef conservation management strategies. Through embracing the socio-cultural dimensions of coral restoration in goal setting, efficient monitoring of ecological success, improved management and logistics of the day to day practices, improved capacity for local community involvement, and securing long-term funding, coral restoration can be a powerful tool to support resilience and provide hope for the future of coral reefs and the many important benefits associated with them.

CHAPTER 6

Characterising coral restoration effectiveness: social versus ecological realities of coral restoration effectiveness vary across context and stakeholder groups

6.1 Introduction

Rapid increases in climate change-associated disturbances over the past 20 years are re-shaping the world's coral reefs. Across the globe, coral reefs are becoming ghost-like versions of once healthy reefs; characterised by low cover, and lowered biodiversity and functional redundancy of reef-building corals (Gardner et al. 2003, Hughes et al. 2017, McWilliam et al. 2018). One major consequence of these declines is the loss of reef-associated ecosystem services such as food security, commercial opportunities, coastal protection, and strong cultural values (Moberg & Folke 1999, MA 2005). The rapid degradation of coral reefs is driving strong advocacy for intervention strategies, such as reef engineering, to prevent further losses, aid recovery, and boost reef resilience (Anthony et al. 2017, Darling & Cote 2018). Coral restoration is one intervention strategy put forward in the reef engineering toolbox. Yet, whilst it is increasingly used as a reef management strategy worldwide (Young et al. 2012, Rinkevich 2014, Boström-Einarsson et al. 2018), coral restoration is also widely criticised for being time and resource-consuming, as well as for being very limited in the scale of potential benefits (Precht et al. 2005, Edwards & Gomez 2007, Bayraktarov et al. 2016). Moreover, as discussed in Chapter 2, the science underpinning coral restoration efforts, coral restoration ecology, is still in its infancy, and is currently focused on a very technical characterisation of coral restoration success. These limitations hinder our understanding of whether coral restoration is an appropriate, effective tool to aid resilience-based management of coral reefs in a rapidly changing climate.

Characterising coral restoration effectiveness in the context of reef resilience is a complex exercise (Edwards & Gomez 2007, Chapter 2 section 2.3). In Chapter 2, I reviewed the literature and presented six common objectives of coral restoration and developed 10 indicators of coral restoration effectiveness in the context of reef resilience across socio-ecological dimensions (Figure 2.4). These indicators were proposed as objective tools for managers to measure the success of their efforts. In Chapter 3, I was able to show that the restoration efforts at four well-established coral restoration programs provided long-term increases in hard coral cover and structural complexity at restored compared to unrestored sites. Yet, the four programs did not perform equally across the different indicators; further analysis revealed that the effectiveness of coral restoration was highly context-dependent (Chapters 3 to 5). For example, the abundance of small fish was only increased at restored sites when a range of different artificial structures were used as restoration substrates (Chapter 4, section 4.3). Additionally, in the Caribbean, the potential for capacity-building was limited because the restoration efforts were subject to strict permit limitations and legislative regulations (Chapter 5, section 5.3).

Importantly, coral restoration effectiveness is not just context-dependent, it is also likely to vary according to local stakeholders' perceptions of success (Chapter 5, section 5.3). Perceptions have recently been identified as very important drivers of the success of conservation management strategies (Jähnig et al. 2011, Brancalion et al. 2014, Sainsbury et al. 2015, Bennet 2016). Ultimately, success requires the support and engagement of local stakeholders, and a working understanding of their subjective perceptions if restoration outcomes are to be defined and achieved (Bennet 2016, Sterling et al. 2017). This is very important when assessing the effectiveness of socio-cultural and economic restoration outcomes (Jähnig et al. 2011, Brancalion et al. 2014). For example, Jähnig et al. (2011) found a disconnect between biological measurements of river restoration success and managers' perceptions, with managers tending to overestimate the success of river restoration efforts. They argued that subjective success indicators, such as aesthetics, should be used as additional indicators of restoration success to supplement biological measurement and better encompass stakeholders' perceptions (Jähnig et al. 2011). Moreover, understanding local stakeholders' perceptions of restoration success is critical to better integrate their needs in the planning of conservation efforts (Al-Agwan 2015). For example, different stakeholders (i.e., researchers versus program volunteers) might perceive the importance of outcomes differently across the range of potential benefits of coral restoration. In Chapter 5, I suggested that the perceptions of coral restoration's benefits and limitations encompass far more than ecological considerations, and include all four dimensions of sustainability: ecological, socio-cultural, governance, and economic (Valentin & Spangenberg 2000). These four dimensions are already integrated in the goals and definition of ecological restoration (Jellinek et al. 2013, Perring et al. 2015, Martin 2017), yet, coral restoration ecology is still largely focused on measuring ecological outcomes only (Chapter 2, section 2.3). Better understanding context-dependency and the range of perceptions of coral restoration effectiveness across these four dimensions is thus critical to elucidate some of the complexities, and understandings behind the ratings of coral restoration success.

In this Chapter, I first aim to assess the context-dependency and range of stakeholders' perceptions of coral restoration success across socio-ecological scales at four well-established coral restoration programs. More specifically, I aim to better understand stakeholders' perceptions of the importance of coral restoration across the four dimensions of sustainability (ecological, socio-cultural, governance, and economic), and how these perceptions might vary across different programs or different groups of stakeholders. Secondly, I also aim to compare perceptions of success to the in-situ measures of ecological changes described in Chapters 3 and 4 in order to understand the extent to which stakeholders' perceptions match the ecological results found in this study.

6.2 Methods

Four well-established coral restoration programs were used as case-studies for this Chapter: New Heaven Reef Conservation Program (Koh Tao, Thailand), Reefscapers (Landaa Giraavaru, Maldives), the Coral Restoration Foundation (Florida Keys, USA), and The Nature Conservancy Caribbean Program (St Croix, US Virgin Island) (See Chapter 3, section 3.2.1, and Chapter 5, Appendix 1 for further details on each of the programs).

Face-to-face, key-informant interviews were conducted at each of the four locations to assess local stakeholders' perception of the benefits and limitations of the coral restoration programs (See Chapter 5, section 5.2 and Appendix S5.1 for details on the interview design, administration and analysis).

6.2.1 Perceptions of the importance of the coral restoration programs across the four dimensions of sustainability

In Question 5.a, respondents were asked to rate the importance of the coral restoration programs for each of the four dimensions of sustainability: ecological dimension, socio-cultural dimension, economic dimension, and governance dimension. Scores were given from one to 10 where one is "not important at all" and 10 is "extremely important". Scores were then grouped into the following categories of importance: "low" (1 to 3), "medium" (3 to 7), and "high" (7 to 10). Scores of importance were then compared among locations and groups of respondents using general linear models, as well as planned contrast matrices.

Question 5.a was also open-ended, allowing each respondent to justify their grade if they wished to do so. Such responses were analysed using NVivo (Version 11.4.2 (2018)) using content analysis. For each dimension of sustainability, responses were first coded as either "positive" or "negative", and then further coded into sub-themes (coding groups). The coding groups were then checked with co-investigators to ensure that each coding group was as independent as possible, and that all responses were accounted for. Coding was an iterative process, and co-investigators were repeatedly consulted to ensure homogenous interpretation and description of each coding group. The total number of sources (i.e., number of respondents), and references (i.e., numbers of citations) were also recorded for each coding group across all respondents.

6.2.2 Ecological indicators: perceptions versus ecological measurements

6.2.2.1 Stakeholders' perception of change between natural and restored areas

In Question 2.d, respondents were asked to rate the natural reef of the given location for seven metrics of reef performance while in Question 3.c, respondents were asked to rate the restored reef of the given location for the same seven metrics. Stakeholders' perception of change between natural and restored areas were characterised by comparing answers to these two questions. The seven metrics of reef performance were: 1) beauty, 2) coral abundance, 3) fish abundance, 4) abundance of other organisms, 5) coral diversity, 6) fish diversity, and 7) diversity of other organisms, and each metric was scored from one to 10, where one was generally considered as “extremely bad” and ten was “extremely good”. For example, their perception of “Beauty” was assessed on a scale of one to ten, where one was “not at all beautiful” and ten was “the most beautiful reefs I have ever dived” (Q2.d.1, Appendix S5.1, Section 2). Prompts and flashcards were used to guide the respondents. For example, A linear scale running from 1-10 was presented to respondents on a laminated A4 sheet of paper to provide some visual reference to the respondent.

Scores for each metric were then compared between restored and natural areas using general linear models in the statistical program R (version 3.4.1, RStudio Team 2015). Comparisons among different groups of respondents and among locations were also performed using planned contrast matrices.

6.2.2.2 Comparisons with ecological data

Perceptions of change from the interview data were compared to changes measured in underwater surveys between restored and unrestored areas for four metrics: 1) coral abundance, 2) coral diversity, 3) fish abundance, 4) fish diversity (See Chapter 3, Section 3.2 for details on the method used to collect data on the benthic assemblages, and Chapter 4, Section 4.2 for details on the method used to collect data on the fish communities).

6.3 Results

6.3.1 Perception of the importance of the coral restoration programs across the four dimensions of sustainability

6.3.1.1 Key positives and negatives for all four categories

Ecological importance

The ecological importance of coral restoration was rated as “high” by over 86% of the respondents across all locations (Figure 6.1A. The sub-theme “for the reef” was the most common sub-theme mentioned as positives. For example, one respondent mentioned:

“*We need somehow to build our reef. There is no other way. We need to attach the corals to the reef and it can grow*.” LG22TI

Other positive sub-themes included “for the action”, “for the corals”, “for the fish” and “for the science” (Figure 6.1A, Table S6.1, Appendix S6).

Less than 1% of the respondents rated the ecological importance as “low”, and 12.5% of the respondents rated it as “medium” (Figure 6.1A. The sub-themes “inadequate scale”, and “outcome uncertainty” were equally as cited for negatives (Figure 6.1A, Table S6.1, Appendix S6).

Socio-cultural importance

The socio-cultural importance of coral restoration was rated as “high” by 87% of the respondents across all four locations (Figure 6.1B). The most common sub-themes for positive statements were related to “education”:

“*The idea is not just to restore the environment but also teach people how to conserve it and how to take care of the environment*." LG07DI

Other sub-themes for positive statements included “awareness” and “stewardship” (Figure 6.1B, Table S6.1, Appendix S6).

Like the ecological importance, the socio-cultural importance was never rated as “low”, but 13% of the respondents gave “medium” scores (Figure 6.1B). The most common sub-themes for negatives statements was related to “limited outreach”. For example:

“*I haven’t seen many locals involved*” KT25PV

Other sub-themes for negative statements of the socio-cultural importance of coral restoration included “limited education” and “limited drawbacks” (Figure 6.1B, Table S6.1, Appendix S6). “Limited drawbacks” referred to a potential for people to use coral restoration as an excuse not to address bigger issues. For example, one respondent said:

"*There's actually some people out there who use it as fuel against restoration. They'll say that if too many people feel like "All we have to do is plant new corals and it will fix all the problems", they will stop being concerned about burning too much fuel or you know, wearing the wrong sunscreen which can have impacts, or other things*" FK12CP

Economic importance

The economic importance was rated as high by over 56% of the respondent, "medium" by 40.6% of the respondents, and "low" by 2.8% of the respondents across the four locations (Figure 6.1C). Positive statements were mostly related to economic benefits "for the tourism industry" including the diving and the recreational fishing industries:

"*It is important for all the fisheries and the dive… because diving here is huge, it's what people come in the Keys to do. There is no beach, so you have to go diving.*" K01PI

Other economic benefits were "for people involved" (e.g. program staff), "for the local economy" (e.g. fisheries, restaurants), and "for ecosystem processes" (e.g. coastal protection) (Figure 6.1C; Table S6.1, Appendix S6).

Negative statements related to economic benefits referred to limitations in the scale of benefits (i.e., how far the benefits can spread away from the program itself), as well as to a limit in the economic benefits since the restoration efforts are expensive on their own (Figure 6.1C; Table S6.1, Appendix S6).

Governance importance

The governance importance was rated as high by over 65% of the respondents, "medium" by 29.9% of the respondents, and "low" by 4.6% of the respondents across the four locations (Figure 6.1D). Positive statements related to the importance of coral restoration for improved governance included "to get institutional support" and "for institutional support" (Figure 6.1D; Table S6.1, Appendix S6). The former referred to how the ongoing coral restoration efforts have been instrumental in gathering support from governmental institution. For example, one respondent stated:

“*Critical for making the permitting easier, making the funding easier, and yeah, no absolutely, and it’s also going to bring larger awareness to a larger audience if it can reach that sort of level as well.*" KT12CP

The sub-theme “for institutional support” referred to evidence that the coral restoration efforts are supported by executive institutional bodies:

"*We just got that enormous NOAA grant. And we’re basing our efforts on an Acropora recovery plan which nobody has ever done before. And both of those come from government agencies* " FK11PS

Negative statements relating to the importance of governance were expressed as “support is insufficient” in reference to limited funding and/or legislative support from institutions:

“*There is no real support for conservation*” LG01PS;

Other negative statements were expressed as “support is inadequate” in reference to disconnects between the institutional framework and the support required to help the restoration efforts (Figure 6.1D Table S6.1, Appendix S6).

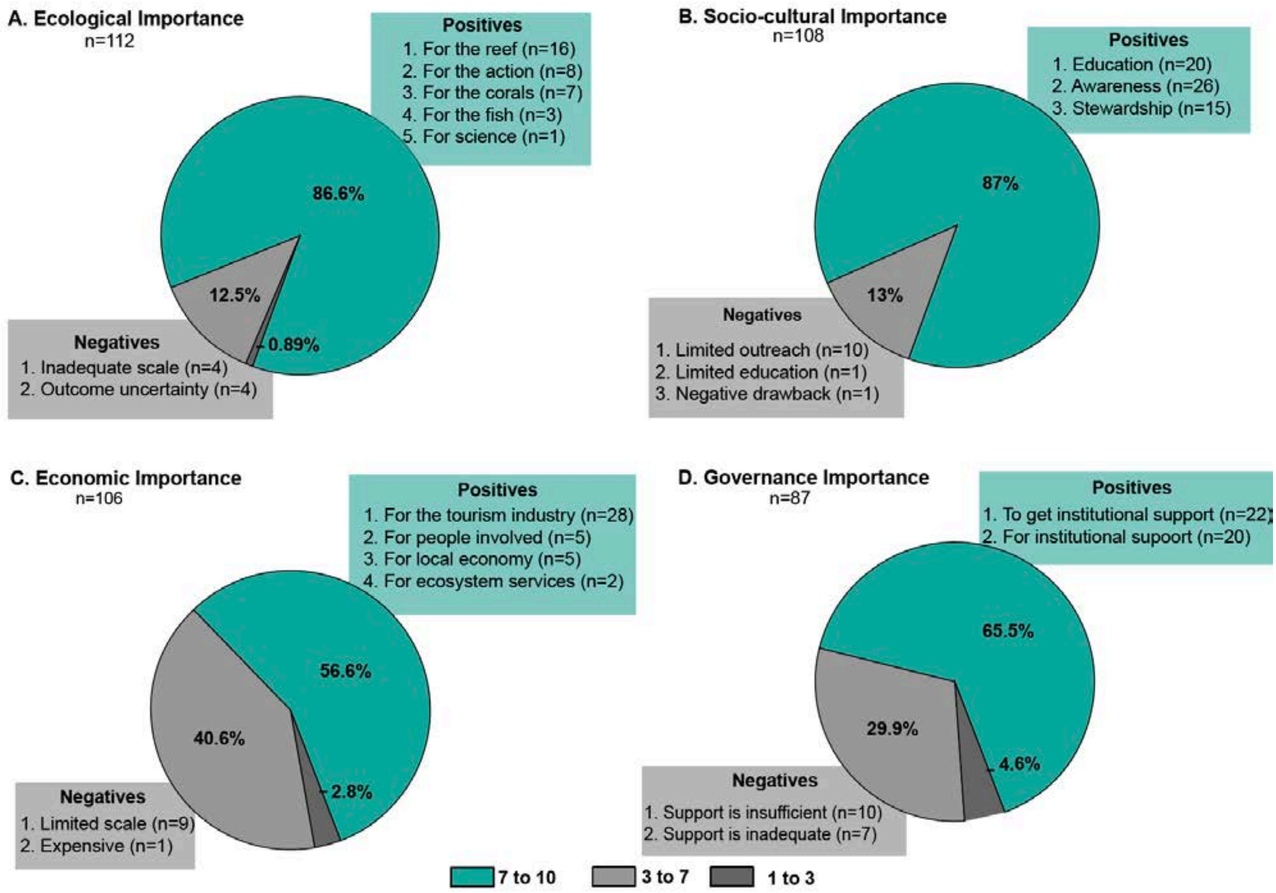


Figure 6.1 Proportion of respondents rating each category of importance as “high” (7 to 10), “medium” (3 to 7), or “low” (1 to 3), as well as key sub-themes identified for responses associated with positive and negatives perceptions

6.3.1.2 Location-specific variations

The average score across all four categories was 8.3/10. Scores for socio-cultural and ecological importance were significantly higher than scores for economic and governance importance across all four locations (Figure 6.2). Socio-cultural importance was rated highest in the Florida Keys and Landaa Giraavaru, while ecological importance was rated highest in Koh Tao and St Croix, but differences in scores between these two categories were never significant (Figure 6.2). Scores for economic importance were the lowest at all programs except in Koh Tao where scores for governance importance were the lowest (Figure 6.2).

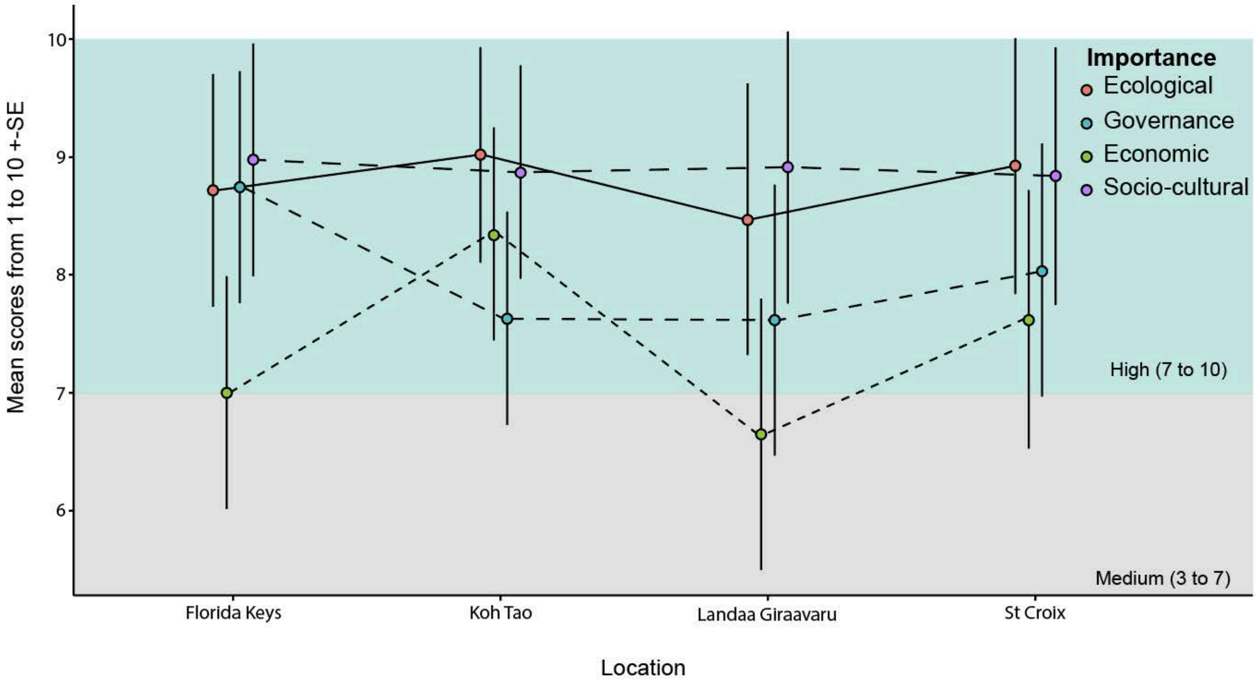


Figure 6.2 Scores of importance of coral restoration for four categories: Ecological, Socio-cultural, Governance, and Economic at all four program locations. Vertical lines crossing horizontal lines indicates non-significance

6.3.1.3 Group-specific variations

Ratings of coral restoration importance also varied among groups of respondents. Conservation practitioners gave significantly lower scores than program volunteers and members of the diving industry overall (Figure 6.3). Socio-cultural and ecological importance were rated highest by all groups, except conservation practitioners who rated governance importance higher than ecological importance (Figure 6.3). Economic importance was graded as significantly lower than ecological importance by three groups of respondents: tourism industry members, program staff, and members of the diving industry. These same groups as well as conservation practitioners also rated economic importance as significantly lower than social importance.

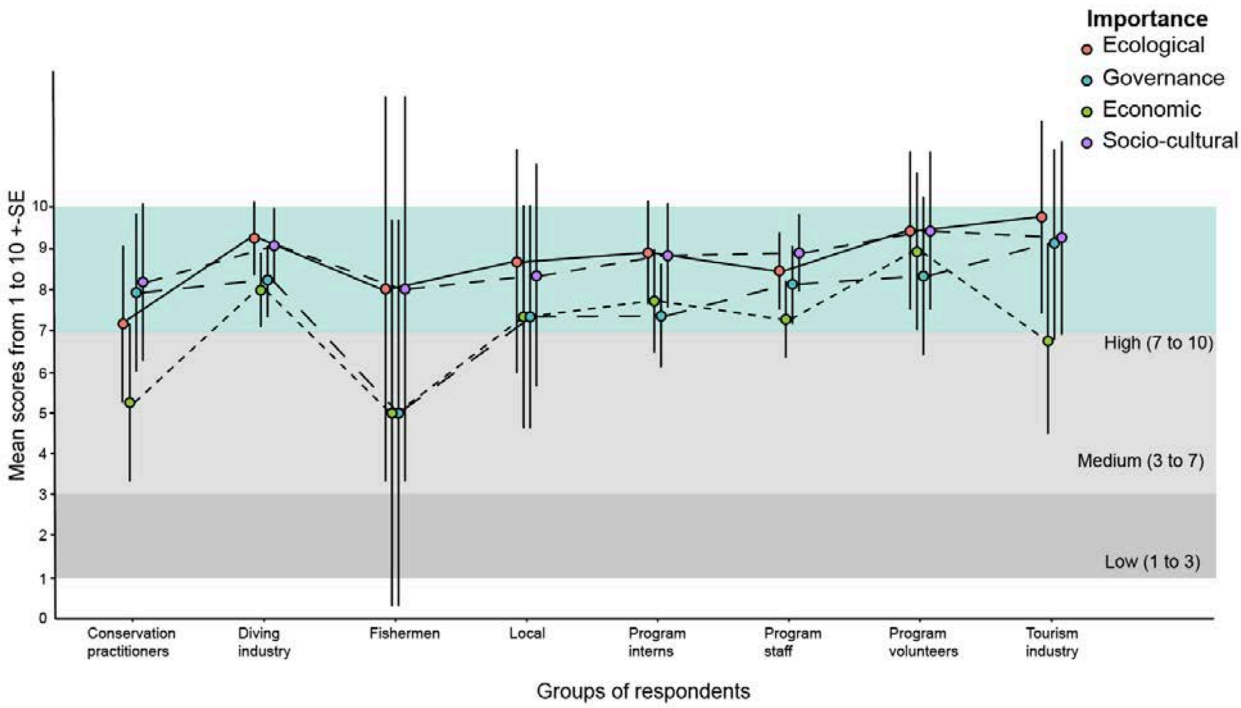


Figure 6.3 Scores of importance of coral restoration for four categories: Ecological, Socio-cultural, Governance, and Economic for all different groups of respondents across all four program locations. Vertical lines crossing horizontal lines indicates non-significance

6.3.2 Ecological indicators: perceptions versus ecological measurements

6.3.2.1 Seven metrics of change

Total scores for the metrics of reef performance did not vary between restored and natural areas (LM, F=0.013, p=0.91, Figure 6.4). Among the seven metrics, two metrics, beauty and coral abundance, were graded significantly higher in restored than natural areas (Beauty: LM, F=4.76, p=0.03; Coral abundance: LM, F=8.08, p=0.005; Figure 6.4). There was no difference in scores between restored and natural areas for the other five metrics (Figure 6.4). However, these trends varied among locations, as well as among groups of respondents.

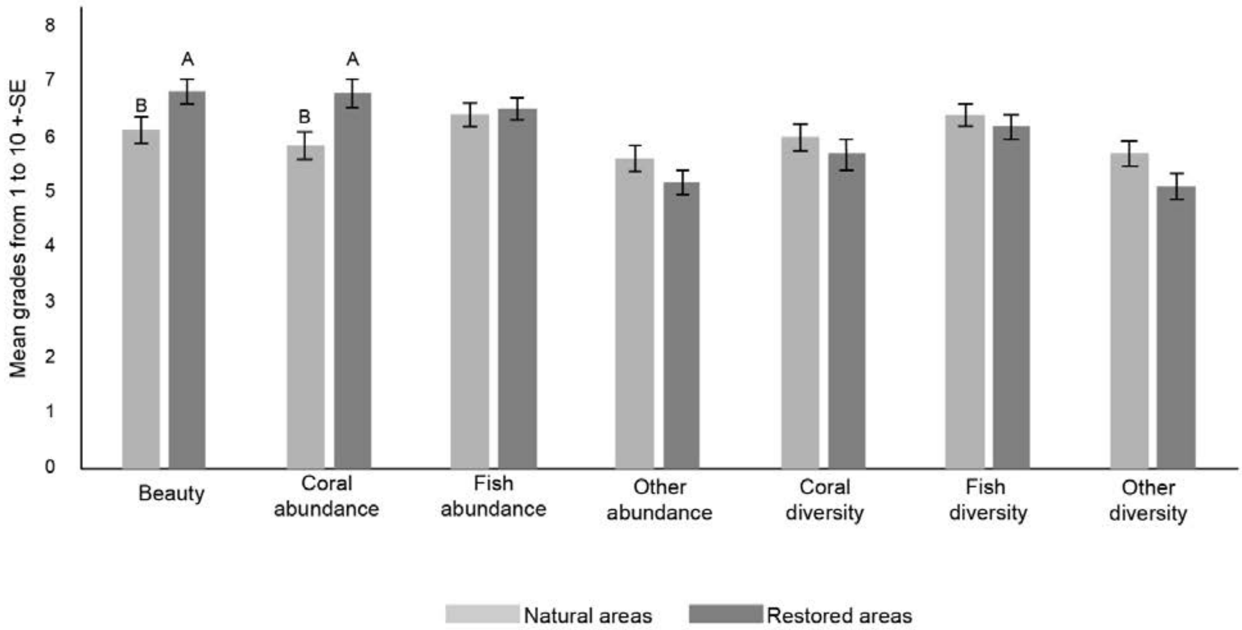


Figure 6.4 Mean scores for the seven metrics of reef performance between natural and restored reef areas at all four locations surveyed (n=58 respondents). Letters refer to Tukey's HSD post-hoc test indicating significance

Location-specific variations

The scores for reef performance metrics did not vary consistently among the four locations (Table 6.1). Beauty and coral abundance were rated higher in restored than natural areas at all four locations, but the difference in scores was only significant in the Florida Keys (Table 6.1). In Landaa Giraavaru, scores for both coral and fish diversity were significantly lower in restored compared to natural areas, while in Koh Tao, it was the scores for the abundance of other organisms that were lower in restored than natural areas (Table 6.1). In St Croix, on the other hand, scores for fish abundance were significantly higher in restored compared to natural areas (Table 6.1).

Table 6.1 Table showing the ratio of difference in scores between restored and natural areas for all seven metrics of reef performance at all four program locations. Coloured boxes represent the significance of the difference: green denotes significant positive ratios; red denotes significant negative ratios, blue denotes non-significant differences

	Koh Tao-Thailand	Landaa Giraavaru-Maldives	Florida Keys-USA	St Croix-US Virgin Islands
Beauty	+1.03	+1.04	+1.28*	+1.06
Coral abundance	+1.05	+1.09	+1.42*	+1.11
Coral diversity	1	-0.77*	-0.99	-0.95
Fish abundance	-0.95	-0.93	1	+1.22*
Fish diversity	-0.98	-0.84*	+1.03	-0.97
Other abundance	-0.84*	-0.85	1	-0.99
Other diversity	-0.88	-0.89	-0.99	-0.83

Group-specific variations

Most of the groups of respondents rated the reef performance metrics similarly between restored and natural areas, except program staff who rated coral abundance as higher in restored areas, and program interns who rated the abundance of other things as higher in natural areas (Table 6.2).

Table 6.2 Table showing the ratio of difference in scores between restored and natural areas at the four program locations for all seven metrics of reef performance for seven groups of respondents. Coloured boxes represent the significance of the difference: green denotes significant positive ratios; red denotes significant negative ratios, blue denotes non-significant differences

	Conservation practitioners	Diving industry	Local	Program interns	Program staff	Program volunteers	Tourism industry
Beauty	+1.12	+1.17	1	+1.03	+1.13	1	+1.17
Coral abundance	+1.33	+1.13	-0.85	+1.05	+1.26*	+1.18	+1.36
Coral diversity	+1.14	-0.94	-0.83	-0.91	-0.99	+1.10	-0.58
Fish abundance	+1.27	-0.98	+1.14	-0.92	+1.08	-0.88	+1.06
Fish diversity	+1.11	-0.97	1	-0.95	-0.94	-0.95	-0.97
Other abundance	1	+1.03	-0.83	-0.75*	-0.95	-0.97	-0.92
Other diversity	1	-0.94	-0.83	-0.78	-0.89	-0.94	+1.04

6.3.2.2 Comparison with in-situ ecological data

Respondents' scores did not match ecological data for coral diversity in the Florida Keys and St Croix, for fish abundance in Koh Tao and the Maldives, and for fish diversity in Koh Tao and St Croix (Table 6.3). For the other metrics, respondents' scores matched the direction of change measured in-situ. Yet the significant positive increases in coral abundance were only perceived as significant by respondents in the Florida Keys (Table 6.3). Some metrics were also significantly different in the social survey but not in the ecological surveys such as perceived increases in fish abundance in the restored areas in St Croix, and a perceived decrease in fish diversity in Landaa Giraavaru (Table 6.3).

Table 6.3 Table comparing ecological measurements and scores from respondents for four reef performance metrics at all four program locations. Values represent ratio of change at restored compared to unrestored sites. Coloured boxes represent the significance of the difference: green denotes significant positive ratios, red denotes significant negative ratios, blue denotes non-significant differences. Scores in red font refer to differences in the direction of change between ecological and social measurements

		Koh Tao-Thailand	Landaa Giraavaru-Maldives	Florida Keys-USA	St Croix-USA
Coral abundance	Ecological measurements	+3.35*	+3.11*	+5.25*	+1.5
	Respondents grades	+1.05	+1.09	+1.32*	+1.11
Coral diversity	Ecological measurements	+1.26	-0.63*	+1.17	+1.06
	Respondents grades	1	-0.77*	-0.99	-0.95
Fish abundance	Ecological measurements	+2.18	+1.32	-0.77	+1.20
	Respondents grades	-0.95	-0.93	1	+1.22*
Fish diversity	Ecological measurements	+1.10	-0.98	+1.02	+1.17
	Respondents grades	-0.98	-0.84*	+1.03	-0.97

6.4 Discussion

This study provided a unique opportunity to assess local stakeholders' perceptions of coral restoration effectiveness across four restoration programs for which effectiveness was also measured in-situ ecologically. Results reveal that ecological and socio-cultural importance are systematically perceived as very important to coral restoration effectiveness regardless of the context or stakeholder group. However, perceptions of economic and governance importance varied among programs as well as among stakeholder groups. Perceptions of the ecological effectiveness of the programs were also context- and group-dependent and did not always match the ecological measurements taken in situ. Altogether, the results confirmed the hypothesis that coral restoration effectiveness is both stakeholder- and context-dependent.

6.4.1 Importance across the four dimensions of sustainability

A critical finding from this work was that both socio-cultural and ecological importance were rated as “high” by over 86% of the respondents, across all locations and groups. These results reinforce the idea that the perceptions of coral restoration effectiveness range far beyond ecological considerations alone (Chapter 5). In particular, the capacity of coral restoration to provide education, awareness and stewardship is perceived as equally as important as its capacity to improve the condition of coral reefs. The importance of socio-cultural aspects of coral reef restoration programs is probably linked to the practical, “hands-on” experiences that are likely to promote education and stewardship (Hesley et al. 2017, Dean et al. 2018).

While economic and governance were generally not rated as highly as ecological and socio-cultural importance, they were still both rated as “high” by over 56% of the respondents. These results highlight that, again, perceptions of coral restoration effectiveness range across all four dimensions of sustainability (Chapter 5). Governance importance was rated highest in the Florida Keys, where the restoration efforts are most limited by permit restrictions and funding from government agencies. It thus appears that in the Florida Keys, effectiveness at the governance level is probably playing an important role on the ecological outcomes of the coral restoration efforts. The findings are in line with studies by Miller et al. (2015) and Eklund & Cabeza (2017) who found that conservation outcomes were linked to governance effectiveness. Economic importance, on the other hand, was rated highest in Koh Tao, Thailand out of the four case studies. Koh Tao is one of Asia’s top destinations for tourism, especially geared towards the scuba-diving industry providing the second-highest number of diving certifications every year behind Cairns, Australia (Wongthon & Harvey 2104). It is thus possible that out of the four case studies, Koh Tao is where local stakeholders are most reliant on the reef for their livelihoods, and thus most likely to realise the economic importance of the ecological outcomes of the coral restoration efforts. These results thus suggest that whilst economic incentives are central to the goals of restoration (Keenleyside et al. 2012), the recognition of coral restoration's economic importance can be context-dependent (Nielson et al. 2016).

Ratings of importance across the four dimensions of sustainability were not just context-dependent but also varied among different groups of stakeholders. These variations illustrate the subjectivity of perceptions of coral restoration effectiveness among stakeholders. In a study on the perception of river restoration success, Jähnig et al. (2011) found a mismatch between the perceptions of the public focused on aesthetics and that of managers focused on biophysical parameters. Here, respondents who were directly involved in the restoration efforts (program staff, program volunteers, and program interns) rated the four categories of importance similarly, while the rates were more variable among the other groups. Conservation practitioners in particular, rated governance importance higher than ecological importance, which implies that they recognised the importance of good management and legislative support as integral to the success of the restoration efforts. Several groups (tourism industry, dive industry, program staff, and conservation practitioners) rated economic importance as significantly lower than both ecological and socio-cultural importance. These results imply either that they do not see economic gains as part of the objectives of the restoration efforts (i.e., they're not in it for the money), or that economic benefits from the restoration efforts are not substantial enough to be perceived as important. The latter is particularly relevant for the dive and tourism industries since they are the two groups most likely to benefit economically from the ecological outcomes of the coral restoration efforts. Negative statements related to economic importance mentioned the limited scale of the spread of the potential benefits, reinforcing the idea that economic benefits are not necessarily felt outside of the restoration program. While coral restoration programs have the potential to yield substantial economic benefits (Edwards et al. 2012), the active involvement of local stakeholders in the programs is crucial for the benefits to be perceived within the community (Kittinger et al. 2016). Restricted involvement of the local communities was one of the most important limitations to the success of the restoration programs surveyed here (Chapter 5, section 5.3.2), and may explain the lower ratings for economic importance measured within these stakeholder groups.

Altogether, these results echo previous studies that found that benefits from conservation management programs are typically perceived variably by local communities and thus that perceptions of success vary depending on the people asked (Sainsbury et al. 2015, Lau et al. 2017). They also reinforce the benefits of involving a range of different stakeholders in assessing coral restoration success, in order to account for the diversity of perspectives and ensure socio-ecological objectives are met.

6.4.2 Ecological indicators: stakeholders' perceptions versus ecological measurements

Ecological indicators can be measured both objectively and subjectively (Le et al. 2012), yet people's perceptions of ecological outcomes are often overlooked and yet central to the long-term success of conservation initiatives (Bennet et al. 2016). Here, respondents did not seem to perceive a lot of change in reef performance metrics between restored and natural areas, which suggests that the respondents view the ecological impact of the coral restoration efforts as limited overall.

Out of the seven metrics, only ratings for coral abundance and beauty were higher in restored than natural areas overall. The perception of increased coral abundance in restored areas is logical since an increase in coral cover is the most direct effect of coral restoration efforts. Simply put, corals are planted back on the reef, therefore coral abundance increases. These results also corroborate the results from Chapter 3, in which I found increases in coral cover at the restored compared to the unrestored sites at all four locations (section 3.3). The improved perception of beauty in restored compared to natural areas also suggests an overall appreciation of the restoration efforts. Aesthetics are associated with a variety of ecosystem services from recreation, to cultural values (MEA 2005), and improved perception of beauty therefore suggests that coral restoration efforts are satisfying the delivery of these services at the restored areas. Aesthetics perceptions are also an important measure of restoration effectiveness in the public eye (Jähnig et al. 2011).

The lack of perception of a restoration effect on the other five metrics suggests that respondents do not perceive any indirect ecological benefits of the coral planting efforts, such as improved ecosystem functions through increased abundance and diversity of fish and other organisms. These results could be due to a lack of communication between the restoration managers and the local community, and/or a lack of community awareness/understanding, both identified as limitations to coral restoration effectiveness in Chapter 5 (section 5.3.2).

I also found that the perception of ecological effects of coral restoration varied among programs and groups of stakeholders. In both Koh Tao and Landaa Giraavaru, respondents failed to recognise a significant increase in coral abundance at the restored areas. These two programs were also the only two locations where respondents perceived restored areas negatively compared to natural areas for some ecological metrics. Respondents at these locations might perceive the natural areas as in generally good condition, therefore failing to detect some of the effects of the coral restoration efforts. The degradation status of the natural areas is thus likely to play a role in people’s perception of the coral restoration effectiveness, with increased perception of effectiveness in the most degraded areas. In fact, in St Croix, where reefs have suffered extensive damage from tropical storms and outbreaks of coral diseases over the past 20 years (Bythell et al. 2000, Fisco 2008), respondents even perceived significant increases in fish abundance that were not detected ecologically (Chapter 4, section 4.3).
Perceptions of changes were also strongest for people directly involved in the restoration efforts (program staff and program interns). Hands-on involvement can improve education and stewardship (Hesley et al. 2017, Dean et al. 2018), and it is likely that these two groups are better informed than other stakeholders on the ecological outcomes of the restoration efforts. Alternatively, these two groups are also the most likely to be biased towards positive perceptions of the ecological outcomes of the coral restoration efforts,

Respondents’ ratings only matched significant ecological changes between restored and unrestored areas measured in-situ for coral abundance in the Florida Keys, and coral diversity in Landaa Giraavaru. These results highlight a mismatch between stakeholders’ perceptions and ecological measurements at the four programs surveyed. Only people involved first-hand in the restoration efforts perceived significant effects of the restoration efforts suggesting that perceptions of restoration success vary within the different groups of stakeholders. Increased involvement of the community, as well as improved communications of the objectives and results of the coral restoration efforts with local key stakeholders are therefore essential to ensure that perceptions more accurately depict ecological conditions. Positive perceptions and support from local stakeholders are critical to the long-term success of conservation efforts (Bennet et al. 2016), and ultimately to ensure the socio-cultural and economic benefits of restoration meet the actual needs of the local communities (Le et al. 2012).

6.5 Conclusions

Perceptions of coral restoration effectiveness are stakeholder- and context-dependent. Stakeholders across all locations and stakeholder groups provided generally high ratings for both the importance of coral restoration across the four dimensions of sustainability and the metric of ecological outcomes, reflecting overall positive public perceptions of the coral restoration efforts. Yet, informing long-term management of these efforts requires careful evaluation and consideration of context and group-dependent needs, perceptions and expectations (Bennet et al. 2016).

The context of the restoration efforts particularly affected the ratings of economic and governance importance. Economic importance of coral restoration efforts was highest in Koh Tao and Landaa Giraavaru where local livelihoods are most dependent on coral reef resources. Governance importance was rated highest in the Florida Keys where the coral efforts are most affected by permit regulations and capacity for government funding. Context also affected the perception of ecological outcomes of coral restoration, with stronger, positive perceptions in areas where the natural reefs are most degraded.

Ratings were also subjective, dependent on the degree of involvement of the various groups of stakeholders in the restoration efforts and reflected a general lack of community involvement in the restoration programs. For example, tourist operators and the diving industry, which are the groups most likely to benefit from improved reef condition at the restored areas, rated the economic importance as significantly lower than the ecological importance. Program staff and program interns, on the other hand, provided ratings of ecological outcomes that matched the in-situ measures most closely.

Results from this Chapter highlight that there are complex and varied perceptions of coral restoration effectiveness among local stakeholders. As for other conservation management strategies, better understanding and management of peoples' expectations of coral restoration outcomes are crucial for long-term support and success (Brancalion et al. 2014, Bennet et al. 2016). My results suggest that while local stakeholders generally perceive the coral restoration efforts as highly important across all four dimensions of sustainability. Management implications to maximise the successful delivery of socio-cultural and economic outcomes within the respective local communities include: 1) increasing the involvement of the local communities, and 2) improving communications of objectives and results of restoration efforts.

CHAPTER 7

General discussion: effectiveness of the four coral restoration programs across socio-ecological scales and best-practice recommendations

In this study, I developed ten socio-ecological indicators to characterise the effectiveness of coral restoration in terms of the resilience and sustainability of restored communities. I then tested the efficacy of these indicators at four well-established coral restoration programs that differed in geographic location, objectives and methods used. Overall, I found that coral restoration can be a valuable tool to improve coral reef resilience, but outcomes for local reefs and nearby social communities are context-specific and particularly dependent on the design of the restoration program. In this Chapter, I synthesise the results from Chapters 3 to 6 by comparing the outcomes of restoration efforts among the four programs surveyed. I conclude by discussing the implications of these results for management and provide best-practice recommendations for using coral restoration as a tool to improve the long-term socio-ecological resilience of coral reef systems.

7.1 Overall summary

7.1.1 Ecological outcomes of restoration compared among four programs

I considered six ecological indicators based on recommendations by Ruiz-Jaen & Aide (2005) and McClanahan et al. (2012), thus indicators are relevant to measures currently used to characterise the resilience of coral reef systems (McClanahan et al. 2012), as well as to measures of restoration effectiveness used in terrestrial systems (Ruiz-Jaen & Aide 2005) (Chapter 2, section 2.3). Three indicators relate to the structural integrity of the reef (hard coral cover, reef structural complexity, coral diversity), and three relate to reef function (coral health, coral recruitment, and fish abundance), thereby characterising the extrinsic resilience of restored areas at both the colony-scale and reef-scale (Darling & Cote 2018).

Three of the six indicators (hard coral cover, reef structural complexity and fish abundance) were consistent in their response to coral transplantation across all four case studies. Both hard coral cover and reef structural complexity were consistently higher at restored compared to unrestored sites, whereas total fish abundance was unchanged across restoration treatments at all locations (Table 7.1). The greatest increase in hard coral cover detected occurred in the Florida Keys because fragments were transplanted in high densities, whereas coral cover at nearby unrestored local sites is naturally low (Chapter 3 section 3.3, Table 7.1). Increases in reef structural complexity were greatest in Koh Tao because the design of this restoration program involves a mix of different artificial structures (Chapter 3 section 3.3, Table 7.1). Although fish abundance did not differ significantly between restored and unrestored sites at all four locations, mean fish abundance was consistently higher at restored sites in Koh Tao (Chapter 4 section 4.3, Table 7.1). This trend may be attributable to the variety of artificial structures used in the Koh Tao program, which provided a larger range of holes and crevices of different sizes than at other locations. Overall, the lack of significant effect of restoration on fish abundance suggests that the effect of coral restoration on fish communities is limited. It is possible that lack of connectivity to healthy fish populations (e.g. Florida Keys), timing of fish colonisation relative to coral transplantation (i.e., rapid fish colonisation in the first few months post-planting), and species-specific responses of fish to restoration-associated increases in coral cover and complexity (i.e., small coral-associated damselfishes had the strongest response) may account for the lack of effect of coral restoration on fish abundance in this study (Chapter 4, section 4.4). In contrast, all restoration designs explored here were effective at increasing both hard coral cover and reef structural complexity.

Patterns in the other three ecological indicators (coral diversity, coral health, and coral recruitment) varied among the four restoration programs, suggesting that variation in either restoration design or factors relating to their geographic locations affected these indicators. Patterns in coral generic richness spanned all possible outcomes, from significantly improved generic richness at restored sites (Koh Tao), no change (Florida Keys, St Croix), to significant deterioration at restored compared to unrestored sites (Maldives). Identifiable variation in the aims of the four programs is likely to have been a key factor, as the Koh Tao program actively aims to maximise the diversity of corals used in restoration, whereas programs at the two Caribbean locations focus on restoring two endangered *Acropora* species rather than on maximising coral generic diversity. In the Maldives, coral transplants were dominated by fast-growing species in the genera *Acropora* and *Pocillopora* to maximise rates of increase in coral cover over artificial structures. Although this strategy satisfies the aesthetic objectives of the restoration program for hotel guests, it lowered generic diversity at restored sites in comparison to the naturally higher generic diversity at local unrestored sites. The lower generic richness of corals at restored sites in the Maldives represents a trade-off between ecological, socio-cultural and economic objectives at this location.

The only location where the reef-scale indicator, abundance of coral juveniles, was higher at restored sites was in Koh Tao, where a range of different artificial structures was used (Table 7.1). A closer look at the materials and structures deployed suggests that concrete structures, specifically concrete reef balls, are best at enhancing coral recruitment (Chapter 3, section 3.3). Steel frames were not as successful at attracting recruits based on the lack of difference in coral recruitment at restored compared to unrestored sites in the Maldives and at restored sites that only used steel frames in Koh Tao. Poor recruitment overall at both Caribbean locations suggests that coral restoration provides minimal hope for enhancing coral recruitment at depauperate Caribbean sites. Severe limitation in the capacity of Caribbean reefs to produce new juvenile corals may reflect a variety of factors, including lack of larval supply, lack of appropriate settlement surfaces, and/or high mortality of coral recruits (Hughes & Tanner 2000, van Woesik et al 2017).

The impact of restoration on coral health was also variable across programs. Positive effects of restoration on coral health in Koh Tao were associated with a lower prevalence of coral colonies that were compromised by breakage, sand deposits and algal overgrowth at restored sites (Chapter 3, section 3). Transplanting corals onto artificial structures some distance above the substrata is likely to have played a role in mitigating these disturbances. The uniformly poor health of both restored and unrestored corals in the Maldives, where corals are also transplanted onto artificial structures, was unconnected to the restoration program, instead reflecting a mass coral bleaching event at the time of the surveys. Interestingly, coral health was reduced at restored sites compared to both unrestored and reference control sites at both Caribbean locations. The higher prevalence of disease and predation at restored Caribbean sites (Chapter 3, section 3.3) was undoubtedly linked to high densities of fragments in the genus *Acropora,* which has a history of high susceptibility to both disease and predation in the region (Aronson & Precht 2001, Williams & Miller 2012, Miller et al. 2014).

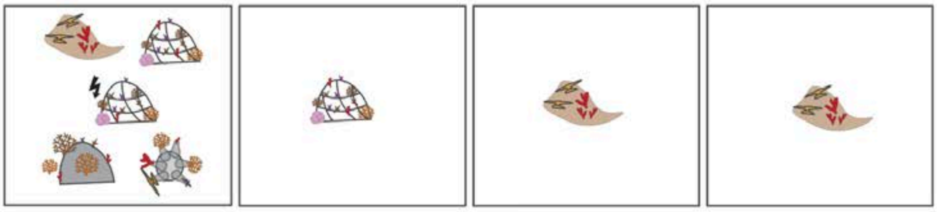
7.1.2 Did restoration improve the ecological resilience of study reefs?

The potential for restoration to improve local ecological resilience was qualitatively estimated based on ratios of metrics calculated for restored to unrestored sites for each of the six indicators (Table 7.1). Positive ratios that represented significant differences between restored and unrestored sites were considered to contribute to a "high" potential for restoration to improve resilience, non-significant ratios represented a neutral capacity to improve resilience, and significantly negative ratios represented a "low" (i.e., weakened) potential for improved resilience (Table 7.1). The mix of positive, neutral and negative ratios for the six indicators at each location was then qualitatively evaluated to derive an overall score that was interpreted as either a strong, moderate or weak (nil) capacity of each of the four programs to improve the ecological resilience of local reefs.

The potential for restoration to improve the ecological resilience of local reefs varied across the four programs, from high in Koh Tao, to moderate in the Maldives and the Florida Keys, to low in St Croix (Table 7.1). In Koh Tao, improvements in indicators associated with both structural (hard coral cover, structural complexity, coral diversity) and functional (fish abundance, coral health, coral recruitment) resilience contributed to the high potential of this program to enhance the ecological resilience of restored sites. The moderate potential for restoration programs in the Maldives and Florida Keys to improve the resilience of local reefs reflected findings that only structural ecological indicators were positively impacted by these restoration programs, combined with evidence that some functional indicators were negatively impacted. More specifically, the lower generic richness of corals at restored sites in the Maldives is likely to have negatively affected functional diversity at these sites, as well as their capacity to withstand disturbances (McWilliam et al. 2018). In the Florida Keys, poor coral health at restored sites suggests that although restoration efforts were meeting their objective of enhancing coral cover, especially of endangered Caribbean species of *Acropora*, transplants were not necessarily healthy and unlikely to survive in the long-term. Similar evidence of poor health of coral transplants in St Croix, combined with lack of change in coral cover at restored compared to unrestored sites underscores the low potential of this program to improve reef resilience (Table 7.1)

Table 7.1 Summary table comparing six ecological indicators used to characterise the effectiveness of four coral restoration programs to enhance the resilience of local reefs. Numerical values represent ratios of each metric at restored compared to unrestored sites. Coloured boxes represent whether or not restoration significantly improved metrics at restored sites, where: green denotes significantly positive ratios, red denotes significantly negative ratios, and blue denotes non-significant differences. Overall estimates of ecological resilience represent qualitative assessments of the potential for the mix of High, Nil and Low ratios of the six indicators to enhance local reef resilience.

Green: High
Blue: Nil
Red: Low



	Koh Tao-Thailand	Landaa Giraavaru-Maldives	Florida Keys-USA	St Croix-US Virgin Islands
Hard coral cover	+3.38*	+3.11*	+5.25*	+1.50
Structural complexity	+2.23*	+2.13*	+1.29*	+1.61*
Coral diversity	+1.26	-0.63*	+1.17	+1.06
Coral juveniles	+14.4*	+1	NA	NA
Coral Health	+1.57*	-0.94	-0.97*	-0.97*
Total fish abundance	+2.07	-0.80	-0.82	+1.22
Ecological resilience estimate	Strong	Moderate	Moderate	Weak

7.1.3 Socio-cultural and economic outcomes of coral restoration compared among four programs

I used four indicators to measure local stakeholders' perceptions of the socio-cultural and economic outcomes of coral restoration: satisfaction (with restoration outcomes), stewardship (of the reef, as related to education or skills acquired as a consequence of restoration programs), capacity building (as related to improved governance and ownership of reef resources as a consequence of restoration programs), and economic benefits (accruing from restored reefs). Characterising the effect of coral restoration on each of these four indicators through surveys of local key stakeholders' perceptions of coral restoration enabled me to address each of the four dimensions of sustainability described in Valentin & Spangenberg's (2000) sustainability framework (i.e., environmental, socio-cultural, governance, and economic dimensions).

All four socio-economic metrics indicated that local stakeholders attached high importance to coral restoration (Table 7.2). Mean scores for satisfaction, measured as stakeholders' perceptions of the overall importance of restoration efforts (i.e., mean scores across all four metrics, Chapter 6, section 6.3), were consistently "very high" for all four programs (Table 7.2). Such positive perceptions suggest that coral restoration has the potential to improve the wellbeing of local stakeholders in the four reef regions studied (Millenium Ecosystem Assessment 2005; McAllister 2005; Larson 2010). Similarly, stakeholders systematically rated the potential of restoration efforts to improve reef stewardship by nearby communities (i.e., scores for socio-cultural importance of reef restoration efforts) as of the highest importance (Table 7.2). This is strong evidence of the capacity of restoration programs to engage with local communities and provide education and awareness of conservation issues.

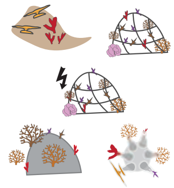
The potential for restoration programs to build local capacity, measured as perceptions of the importance of restoration programs to affect the local governance of reef resources (Chapter 6, section 6.3), was rated as high to very high across all four programs (Table 7.2). Restoration efforts were perceived to enhance local management and governance of reefs on two levels, i.e., restoration programs 1) raised awareness of conservation issues at the institutional level, and 2) consolidated institutional support for reef conservation (Chapter 6, section 3). The importance of restoration programs to improve governance and capacity building was rated highest in the Florida Keys and St Croix, where restoration is most limited by permit regulations and dependent on government funding.

Finally, scores for economic benefits associated with restoration programs were high across all four programs (Table 7.2), even if concerns were raised about the limited scale of benefits arising beyond the actual restoration program (i.e., limited flow-on benefits to the local community, Chapter 6, section 6.3). Scores varied among locations, from highest in Koh Tao where local stakeholders rely heavily on reef resources for their livelihoods (Chapter 6, section 6.3). While the cost-effectiveness of coral restoration is much-debated (e.g. Bayraktarov et al. 2015), these results suggest that economic benefits of restoration do flow on to nearby communities in the long term, especially when programs have been established for some time.

7.1.4 Did restoration improve the socio-cultural and economic resilience of nearby communities at the four restoration programs?

All four socio-cultural and economic indicators studied here confirm that the outcomes of coral restoration were highly valued by local stakeholders at all four locations. There is thus great potential for coral restoration programs to improve the socio-cultural and economic resilience of nearby communities (Table 7.2). Results from Chapter 6 (section 6.3) highlight that perceptions of coral restoration effectiveness varied among locations and groups of stakeholders and are thus subjective and context-dependent. Thus, to maximise the positive effects of coral restoration on the resilience of local communities, a good understanding of the expectations of local stakeholders, as well as of the socio-economic characteristics of the region is required. For example, the many limitations of restoration efforts mentioned by respondents (Chapter 5) suggest that each of these four coral restoration programs could deliver improved outcomes if they embraced socio-cultural dimensions more fully in goal setting, evaluated ecological outcomes more broadly, secured long-term funding, and improved management and logistics of day-to-day practices.

Table 7.2 Table summarising socio-cultural and economic indicators used to characterise the effectiveness of four coral restoration programs at enhancing the resilience of nearby communities. Scores are means (out of 10) and represent the importance that local stakeholders attributed to each metric

				
	Koh Tao-Thailand	Landaa Giraavaru-Maldives	Florida Keys-USA	St Croix-US Virgin Islands
Satisfaction	8.5 /10	8.1 /10	8.4 /10	8.4 /10
Stewardship	8.9 /10	8.9 /10	9.3 /10	8.9 /10
Economic values	8.4 /10	7.1 /10	7.1 /10	7.6 /10
Capacity-building	7.6 /10	7.6 /10	8.8 /10	8.1 /10

Scale	10	Very high	8	High	6	Moderate	4	Low	2	Very low	0

7.1.5 Ten indicators of socio-ecological effectiveness of coral restoration for reef resilience: reflections and limitations

Characterising the effectiveness of four well-established coral restoration programs using these ten indicators has deepened current understanding of how coral restoration can be more effectively used as a tool to promote long-term resilience of coral reef systems and nearby social communities. Importantly, for the first time, outcomes of restoration were assessed at different spatial scales and across different disciplines. Until now, it has been assumed that the benefits of coral restoration are relevant only at limited spatial scales, hence the use of coral restoration to address reef deterioration has been widely criticised (Precht et al. 2005, Edward & Gomez 2007). However, in this thesis, I have demonstrated that benefits can extend beyond localised ecological considerations. In particular, socio-cultural and economic indicators revealed that improved reef stewardship by people involved in hands-on restoration efforts often spreads through local communities, even extending beyond national borders when international volunteers are involved. Although ecological indicators suggested that positive effects of coral restoration accrue mostly at the local scale, with the strongest resilience benefits relating to structural rather than functional attributes, a range of improvements could enhance benefits beyond the direct vicinity of transplanted corals. For example, selecting sites for restoration that are connected to healthy fish populations could enhance the potential for fish to colonise the restored sites (Huntington et al. 2017).

As outlined below, this study highlights a number of limitations in the capacity of coral restoration programs to enhance reef resilience. As well, a number of limitations in my study hampered understanding of the full benefits of coral restoration.

1) Outcomes of restoration were highly context-dependent, varying among programs in response to different methodologies used and/or with geographic variation in reef communities. Accordingly, recommendations outlined in section 7.2 should be generalised with caution.

2) My sampling design for the ecological surveys was not ideal for detecting specific trends across different designs because the type of restoration design, the level of maintenance, and the age of the restored plots all varied within and among sites. In particular, there has been ongoing transplantation at all programs surveyed for the past 8 to ten years. None of the projects were designed as scientific experiments. Studies of different types of artificial structures or of artificial structures versus direct transplantation at one specific location would complement my broad geographic comparisons.

3) The taxonomic resolution of both my coral and fish surveys were low because I wanted to develop indicators that could be easily replicated, standardised and used by reef managers. However, this low resolution hampered the quality of my analysis, especially for fish biomass and diversity. I recommend that future studies focus on fish species, or fish functional groups to gather more detailed information on the response of fish to coral restoration. Genus-level coral data were useful for interpreting trends in coral health but focusing on species-level data is more appropriate to monitor coral diversity patterns, especially for restoration programs focused on restoring endangered coral species (i.e., *Acropora* species in the Caribbean).

4) Another limitation of this study is that I did not compare ecological and socio-economic indicators with respect to baseline targets of success for any of the

indicators. Clear guidelines need to be developed with measurable targets for each indicator, so that assessments of coral restoration success can be standardised and then compared among different projects. These guidelines may include targets that vary with time post-restoration, similar to existing guidelines for terrestrial restoration (see McDonald et al. 2016). For example, a baseline target for coral restoration could be a 50% increase in coral cover at restored compared to unrestored sites, three years post transplantation. Monitoring for coral restoration effectiveness likely involves trade-offs between scientific accuracy and feasibility, as it is both labour- and cost-intensive. Further studies are necessary to assess cost-effectiveness of monitoring efforts and the type of data that are necessary to assess coral restoration effectiveness for specific objectives. For example, indicators such as hard coral cover or reef structural complexity may be assessed more cost-effectively through the use of photo-surveys (e.g. Lirman et al. 2007). Timing of monitoring also requires additional consideration. All ten indicators discussed here may not be relevant for all monitoring phases. For example, measuring for structural ecological indicators may be a priority in the early stages of a restoration project, while functional ecological indicators might be more important in the long-term building phase (2 to 5 years) (Le et al. 2012). Similarly, with socio-cultural and economic indicators, characterising the economic value of restoration efforts, especially how economic benefits are spread throughout local communities, is important in the later phases of restoration projects.

5) The four socio-cultural and economic indicators were measured based on perceptions of local key-stakeholders interviewed in this study. More objective valuations (e.g., full assessment of the economic costs and benefits of each of the restoration programs) are necessary to strengthen understanding of the impact of coral restoration on local communities.

6) Answers to a number of questions on the interview questionnaires did not provide information that was relevant to the research questions addressed in this thesis and thus were not investigated further here (e.g. Q5.c “What do you think the restoration project will look like in 10 years’ time?” or Q5.d “Would you come again”, Appendix S5.1). However, answers to some of the questions not discussed in this thesis provide potentially valuable insights into people’s perceptions of the long-term success of coral restoration efforts, as well as to the utility of intervention strategies in the face of rising climate change-related and anthropogenic pressures to coral

reefs. Responses to these questions will be investigated further, independently from this thesis.

7.2 Management implications and best practice recommendations

Importantly, results from this study have several, direct implications for management that enabled me to develop a set of best-practice recommendations for the use of coral restoration as a tool to improve reef resilience. Existing guidelines for coral restoration are not specifically resilience-focused. Early guidelines from Edwards & Clark (1998) and Edwards (2010) are principally focused on the technicalities of coral transplantation for restoration. Edwards (2010) advocates for the need to clearly define the objectives of a coral restoration program and appropriate monitoring plans over time, but objectives proposed are broad and not explicitly focused on resilience. Other guidelines are regional and species-specific, like the *Caribbean Acropora restoration guide* developed by Johnson et al. (2011).

In contrast, principles and guidelines for ecological restoration (i.e., focused on terrestrial systems) are increasingly focused on resilience and sustainability, and advocate for integrating monitoring for adaptive capacity and for stakeholder engagement (e.g. Perring 2015, McDonald et al. 2016). Resilience is now ingrained as a focal objective of ecological restoration, and it has become the target of a variety of seminal publications highlighting "principles of restoration" (Keenleyside et al. 2012, Perring et al. 2015, Suding et al. 2015, McDonald et al. 2016). A set of principles and guidelines has been published, both for planning for restoration (Suding et al. 2015) and to develop key concepts underpinning best-practices in restoration (Keenleyside et al. 2012, McDonald et al. 2016, Table 7.3)

Table 7.3 Existing principles and guidelines for planning best-practice programs for ecological restoration, as summarised from recent publications

Principles and guidelines	Explanation	Reference
1. Effective	Capacity of program to assess resilience, sustainability, and to monitor for adaptive capacity	Keenleyside et al. 2012
2. Efficient	Cost-effectiveness of program	

3. Engaging	Promote inter-disciplinary collaborations and stewardship by enhancing visitors' experiences	
1. Ecological integrity	Accelerate ecosystem recovery and promote functional diversity and complexity	Suding et al. 2015
2. Long-term sustainability	Create a self-sustainable system so the need for long-term intervention is minimised	
3. Informed by past and future	Adapt historical best-practice to future conditions under climate change	
4. Benefits and engage society	Focus on ecosystem services and human well-being, and actively engage local stakeholders	
1. Reference ecosystem	Native, local, climate change are taken into account	McDonald et al. 2016
2. Have key ecosystem attributes	Ecosystem attributes monitored should inform projects' goals for both short and long-term objectives	
3. Assist natural recovery processes	Help create conditions that make an ecosystem more resilient to climate change disturbances	
4. Seek highest and best effort progression towards recovery	Have step by step recovery evaluation process for long-term adaptive capacity	
5. Use relevant knowledge	Use local knowledge and provide opportunities to enhance outcomes and social benefits	
6. Early, genuine, and active engagement of all stakeholders	Practical collaboration will help develop solutions best suited to the local socio-ecological environment. Increased awareness of both problems and potential solutions	

With managing for reef resilience becoming a major focus of coral reef management agencies (e.g., Maynard et al. 2017), coral restoration ecology needs to develop and embrace resilience-based objectives (Chapter 2, section 2.2). In this study, I have demonstrated that coral restoration can be used as a tool to improve the socio-ecological resilience of coral reefs locally. Using these results, combined with existing guidelines for ecological restoration, I propose a new set of best-practice recommendations for the use of coral restoration to improve coral reef resilience (Figure 7.1). These recommendations incorporate ecological, socio-cultural, governance, and economic characteristics of coral restoration efforts.

7.2.1 Best-practice recommendations for the use of coral restoration as a tool to improve long-term resilience of reefs and nearby communities

Design of coral transplantation efforts: Artificial versus direct transplantation?
The design of coral restoration efforts should strive to maximise reef structural complexity and diversity of the benthic community. Use of a mix of artificial structures, including steel-frames and concrete units, can provide: i) a rapid increase in reef structural complexity, ii) surfaces elevated above the substrate to mitigate sediment and algae overgrowth on coral transplants, iii) surfaces that enhance settlement by coral recruits, and iv) suitable habitat structures for fish to hide and live in (Figure 7.1). Where coral fragments are transplanted directly onto the reef substrata, the density of transplants needs to be optimised to minimise competition among fragments, while maximising habitat production (i.e., increases in coral cover and coral growth) and complexity (Ladd et al. 2018) (Figure 7.1).

Maximising the diversity of transplants at species, phenotypic and genotypic levels is another crucial consideration in the design of restoration efforts (Figure 7.1). High species and phenotypic diversity may enhance the functional redundancy and thereby the resilience of restored areas by attracting more diverse fish assemblages and reconstructing more robust trophic interactions (Shaver & Siliman 2017, Ladd et al. 2018). High genotypic diversity of coral transplants also has the potential to minimise population-wide mortality from disturbances (Jump et al. 2009) and will help identify more resistant genets that can then become priorities for future restoration efforts to further improve the resilience of the system (Reusch et al. 2005, Drury et al. 2017).

Site-selection

Careful site-selection based on connectivity to “healthy” reef areas is essential to enable suites of functional trophic interactions to occur (Figure 7.1). For example, fish recruitment to a restored area is likely to be affected by proximity to healthy areas (Huntington et al. 2017) and to nursery areas (e.g. mangroves and/or seagrasses) (Mumby et al. 2004, Dorenbosh et al. 2007). Connectivity characteristics of restored areas are also central to scaling up the potential benefits of coral restoration, as restored reefs may act as both source and sink reefs for coral larvae. Site selection also needs to account for site-specific characteristics that may promote and/or impede the success of restoration efforts. For example, areas where there is a high density of benthic competitors (e.g. corallimorphs) or corallivores should be avoided (Ladd et al. 2018). On the other hand, sites that have robust, functionally diverse fish assemblages might have built-in resilience, as some fish are natural controls of coral predators and likely contribute to algal removal (Shaver & Siliman 2017, Ladd et al. 2018). Site exposure, proximity to currents, depth, and water quality also require careful consideration (Hernandez-Delgado et al. 2018).

Project logistics

Four key components of the logistics of coral restoration efforts are crucial to maximising long-term socio-ecological outcomes, especially in terms of long-term financial and technical support (Figure 7.1). First, all local stakeholders who are likely to be affected by the restoration effort, either positively or negatively, need to be identified and consulted (McDonald et al. 2016). Long-term support for restoration will depend on stakeholders’ understanding of the project’s objectives and on the alignment of stakeholders’ expectations with them, to ensure they are either unaffected by the project or able to benefit from it (Suding et al. 2015, Sterling et al. 2017). Second, maximising involvement of the local community in restoration efforts is vital to maximise local understanding and stewardship of reef resources (Hesley et al. 2017, Dean et al. 2018). Communicating with members of the local community is also important to share lessons learned and strengthen collaborations (Hernandez-Delgado et al. 2018). Third, securing long-term funding is important. Funding might be provided by participants who are actively engaged in the project, in which case, project logistics need to maximise participants' satisfaction with the program. Alternatively, funding might come from government grants and rely on adequate evidence that the program's objectives are being met. Finally, securing strong leadership and governance is important to maximise the effectiveness and efficiency of restoration efforts, both in terms of logistics, and in managing participants (from staff to volunteers) and to secure long-term engagement and support.

Science

Improving monitoring and research across socio-ecological dimensions is crucial to increase the potential for adaptive capacity and improve understanding of the role of coral restoration in managing the socio-ecological resilience of coral reef systems (Keenleyside et al. 2012, McDonald et al. 2016) (Figure 7.1). Ecologically, indicators should focus on both the structural and functional integrity of restored areas to promote sustained resilience (Ruiz-Jaen & Aide 2005, Hodgson et al. 2015, Maynard et al. 2017). Socio-culturally and economically, monitoring can inform restoration efforts, from the justification for a project to its design, management, and outcomes (Bennet et al. 2016). Cost-benefit and risk analyses are also necessary to better assess the feasibility of coral restoration, and its role in integrated reef management frameworks (Keenleyside et al. 2012, Bayraktarov et al. 2015, Kimball 2015). Coral restoration ecology thus needs to advance towards more multi-disciplinary collaborations.

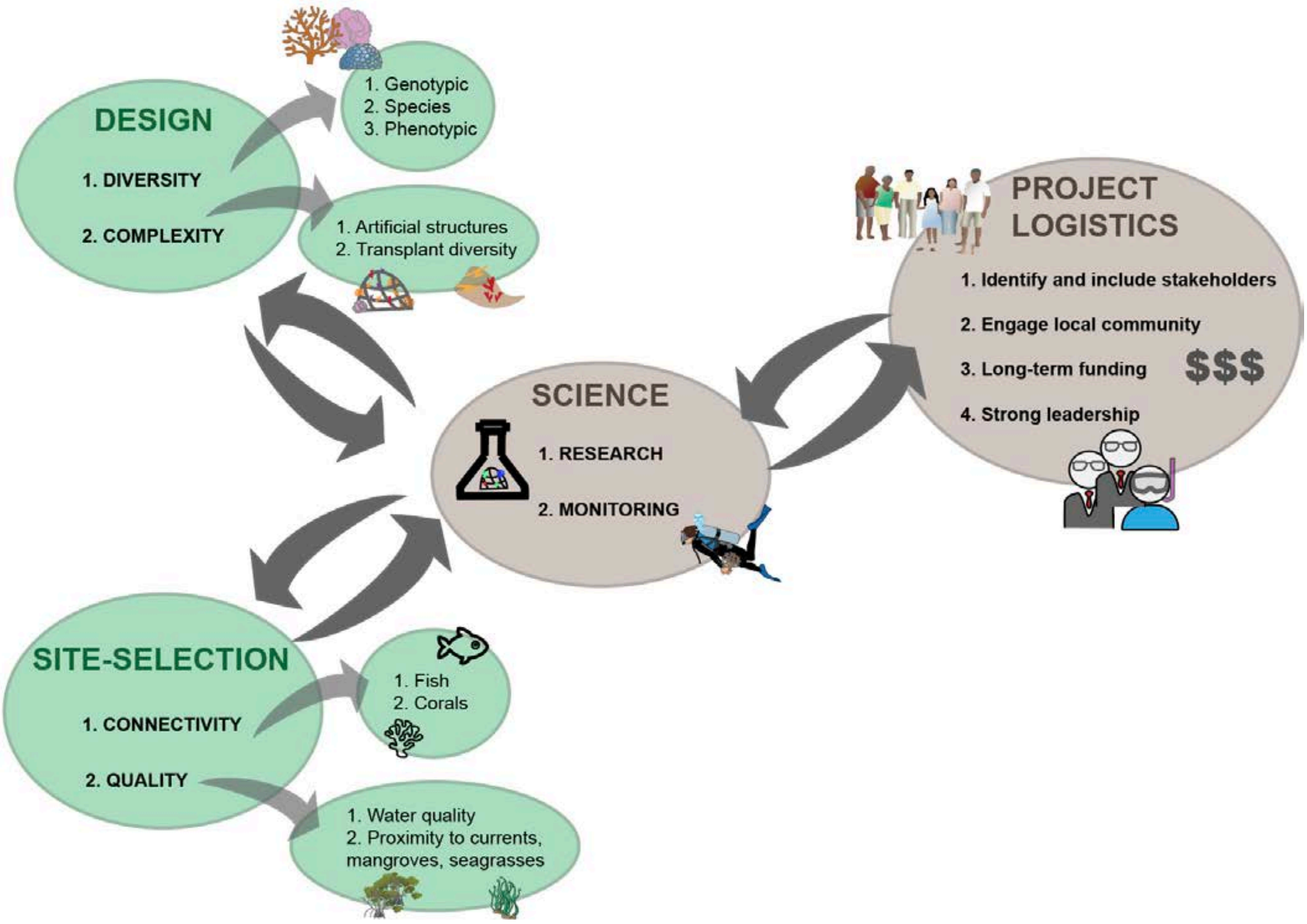


Figure 7.1 Best-practice recommendation framework for the use of coral restoration to improve socio-ecological resilience of reef systems

7.3 Concluding remarks

It has never been more important to characterise the effectiveness of coral restoration than now. Coral restoration ecology is a very young field of science that is currently moving very fast due to rising anthropogenic and climate change-associated disturbances that have greatly accelerated the degradation of coral reef ecosystems over the past 30 years. Coral restoration is increasingly cited as an important tool for reef managers to secure the future of coral reefs, and their associated ecosystem services globally. Objectives for restoration are thus moving away from restoring reefs back to some historic baseline, towards maintaining key structures and functions to support reef resilience in the Anthropocene. Yet, as more intervention options and reef engineering strategies are put on the table (e.g. assisted gene flow, synthetic biology, Anthony et al. 2017), we need to make sure we learn from past mistakes, use sound judgement and best-available knowledge, and adequately invest in monitoring at all stages (Higgs et al. 2018). We must also not lose sight of the greatest threat to coral reef resilience - climate change and associated increases in sea surface temperatures and ocean acidification. Understanding the risks associated with climate change and the best strategies to offset its impacts for coral reefs should be the first and foremost priority of any manager. However, I believe that both climate action and local intervention can be used synergistically. In this thesis, I have shown that coral restoration can be used as a tool to improve the ecological resilience of reefs and the social resilience of local communities. Given the anthropocentric nature of restoration, better characterisation and further improvements in coral restoration effectiveness will require managing people, in equal measure as the reef. Perhaps, then, we can move forward in the development of strategies to protect and restore the reefs we love and rely on.

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APPENDIX S2.1

Section 1: Ecological indicators of coral restoration effectiveness

This section presents the rationale behind the six indicators proposed to characterise the ecological effectiveness of coral restoration efforts.

1. Coral diversity

High coral diversity is typically associated with high habitat diversity and a variety of ecosystem functions (Done et al. 1996; Paulay 1997; McClanahan et al. 2012). Coral diversity is directly linked to reef resilience based on the assumption that the greater the diversity, the greater the variety of responses to stress, and thus the greater the chances for individuals to resist and recover from diverse stressors (Done et al. 1996; McCann 2000; Nyström et al. 2000). Although recent results from a long-term monitoring program, which demonstrated that protected reefs on the Great Barrier Reef characteristically have higher diversity of species and are more resistant to and recover faster from disturbances than unprotected reefs (Mellin et al. 2016), corroborate this line of reasoning, some reefs are resilient without high coral diversity (e.g. Kanehoe Bay; Bahr et al. 2015). On such reefs, monitoring coral diversity would identify the more resilient coral species or genera. In either case, coral transplantation efforts that mimic coral diversity on nearby reference reefs as much as possible, are more likely to restore ecosystem function and avoid genetic bottlenecks (Yap 2000; Edwards & Gomez 2007). In some cases, depending on the initial restoration objective, coral diversity may not be an appropriate measure of coral restoration effectiveness. For example, projects whose goal is to restore endangered coral species have a species-specific transplantation focus. However, such projects are more likely to be successful if the genetic diversity of their transplants is maximised.

2. Herbivore biomass and diversity

Herbivore biomass and diversity are important indicators of reef resilience, as herbivores play a critical role in the removal of algae, thereby providing space for recruitment of corals and other benthic organisms (Hughes et al. 2007). Herbivore diversity is particularly important for increasing the array of herbivory strategies (scrapers, grazers, browsers), which differentially impact benthic organisms (Mantyka & Bellwood 2007; Burkepile & Hay 2008) and promote the resilience of coral reef communities (Burkepile & Hay 2010; Heenan & Williams 2013). Herbivore biomass can be a predictor of benthic cover (Heenan & Williams 2013), and both herbivore biomass and diversity relate to socio-cultural and economic objectives through their links to tourism and fisheries productivity (McClanahan et al. 2012; Maynard et al. 2015). Ideally, herbivore biomass and diversity should be surveyed prior to transplanting corals as part of an assessment for site suitability. Post-transplantation, monitoring herbivore biomass and diversity would allow assessment of whether restoration efforts resulted in fish returning to levels common at reference sites.

3. Benthic cover

Benthic cover is one of the most common metrics surveyed in coral reef monitoring programs (AGRRA-Lang et al. 2010; Reef Check Australia-Hill & Loder 2013). Monitoring benthic cover enables assessment of coral cover in relation to other types of substrata, such as macro-algae, rubble or rocks, and thus provides an overall picture of habitat composition. Macro-algal cover, in particular, is a useful indicator of post-disturbance recovery, with high-resilience sites typically characterised by low percent cover of macro-algae (Cheal et al. 2010; McClanahan et al. 2012; Maynard et al. 2015).

4. Recruitment

Recruitment is a key indicator used to assess the recovery of disturbed reefs, with high levels of recruitment typically linked to increased reef resilience (McClanahan et al. 2012; Maynard et al. 2015). Coral transplantation programs may positively affect coral recruitment through: i) increased coral cover, which increases reproductive output (once the transplants are big enough to release gametes); ii) decreased distances among coral colonies, which increases the likelihood of fertilisation success (Bak & Engel 1979); and iii) decreased macro-algal cover, which increases settlement success (Carpenter & Edmunds 2006). The taxonomic identity of coral recruits can also provide additional information about whether a restored site is likely to be self-recruiting (majority of brooding species) or a sink reef replenished by a healthy source reef (majority of spawning species). Monitoring coral recruitment would thus promote understanding of connectivity patterns and help to predict the long-term trajectory of coral assemblages (Montoya-Maya et al. 2016). Again, levels of recruitment can be highly variable, both temporally and spatially, and I recommend that this indicator be critically assessed against a reference site.

5. Coral health

Coral health is a measure of coral reef stress at the ecosystem level, with a number of studies establishing links between coral disease prevalence and stressors like increasing seawater temperature, sedimentation, and general anthropogenic pressures (e.g. run-off, tourism) (Willis et al. 2004; Heron et al. 2010; Lamb & Willis 2011; Pollock et al. 2014). Potentially, restored coral fragments may have increased disease susceptibility due to transplant stress and transplantation-associated injuries. Transplantation may also disrupt microbial communities associated with coral fragments, potentially enhancing the likelihood of pathogenic infections (Casey et al. 2015). I recommend that monitoring for coral health should encompass diseases, other indicators of compromised health (e.g. predation, algal overgrowth, sediment smothering), as well as physical impacts caused by human activity (e.g. breakage, injuries), as described in Beeden et al. (2008), and Raymundo et al. (2008).

6. Structural complexity

Structural complexity of coral assemblages is associated with increased diversity of coral reef communities, enhancing the diversity of fish populations, and increasing the potential for recovery after disturbances (McCormick 1994; Sleeman et al. 2005; Graham & Nash 2013; Graham et al. 2013; Graham et al. 2015). High structural complexity has also been linked to increased fish biomass, and therefore has important implications for fisheries (Cinner et al. 2009). Structural complexity, as measured on a 0 to 5 point scale, has been identified as a major driver of recovery post-bleaching (Graham et al. 2015).

Section 2: Socio-cultural and economic indicators of coral restoration effectiveness

This section presents the rationale behind each of the four indicators proposed to characterise the socio-cultural and economic effectiveness of coral restoration efforts.

1. Reef user satisfaction

Reef user satisfaction is directly linked to increased wellbeing of stakeholders involved in the restoration effort (Millenium Ecosystem Assessment 2005; McAllister 2005; Larson 2010). Sources of satisfaction may vary among stakeholders. For example, manager satisfaction may be linked to positive ecological changes in the reef ecosystem; local community satisfaction may be linked to increased revenues through alternative livelihood opportunities; and tourist satisfaction may be linked to increased recreational activities (Davis & Tisdell 1995; Pollnac et al. 2001; Pelletier et al. 2005; Okubo & Onuma 2015). Reef user satisfaction is critical to the maintenance of sustainability goals and an important parameter to monitor for integrated, adaptive management.

2. Stewardship

Stewardship is defined by Leopold (1949) as “behaviors that promote sustainable use of resources and conservation.” It is linked to non-use values of ecosystems, such as the existence value (value of the existence and protection of a resource), and bequest value (value of ensuring a resource will be available to future generations) (Samonte-Tan et al. 2007). Stewardship is also linked to educational opportunities associated with local community involvement in coral transplantation programs for coral reef conservation (Okubo & Onuma 2015). Education is fundamental to shifting community focus from ecosystem degradation to protection (Millenium Ecosystem Assessment 2005). Thus building stewardship is an essential component of the long-term sustainability of restoration efforts (Costanza et al. 1998; Costanza et al. 2008; Lirman & Shopmeyer 2016). Monitoring for local reef stewardship could also be done prior to the start of transplantation efforts, as i) the presence of local stewardship would provide initial support for programs, and ii) initial assessment would provide a reference upon which to measure potential increased stewardship in the long term.

3. Capacity building

Capacity building refers to how science, technology and people interact with one another to reach sustainable development goals (UNCED 1992). Increased capacity building has been identified as a key factor underpinning enhanced resilience of socio-ecological systems (Leenhardt et al. 2015). Involvement in coral restoration efforts may foster increased social cooperation among different groups of stakeholders, thereby favoring more sustainable governance of reef resources (Costanza 1999; Schrack et al. 2012). Monitoring for capacity building can identify if coral restoration programs are empowering local communities through training and knowledge and giving them more control over use of reef resources (Le et al. 2012). Also, as described above for the indicator “Stewardship”, monitoring for capacity building would benefit from an assessment of the local governance system prior to the start of the transplantation effort. Not only would this provide a baseline upon which to compare potential changes, but room for capacity building might strengthen support for restoration efforts from external agencies.

4. Economic value

Economic considerations are central to assessing coral restoration feasibility and long-term sustainability of restoration programs (Miller & Hobbs 2007; Bayraktarov et al. 2015; Lirman & Schopmeyer 2016). Valuation of all aspects of a restoration program is needed to comprehensively estimate benefits from both use and non-use values (Spurgeon 2001; Samonte-Tan et al. 2007). Potential benefits should also be assessed against the costs of restoration, including capital costs (e.g. construction costs), operational costs (e.g. monitoring and maintenance), and other costs (e.g. damage to donor site) (Spurgeon 2001; Edwards 2010). Costs are likely to vary greatly depending on the type of restoration technique used, site accessibility, length of monitoring, and the development status of a country (Spurgeon 2001; Bayraktarov et al. 2015).

APPENDIX S2.2

Table S2.1 Table listing all 83 studies related to coral transplantation returned from the search on Web Of Science "Coral* AND Restoration AND Transplantation" along with their primary objective(s), indicator of success used and duration of monitoring in months

Number	Author/Year	Objective	Success indicator	Monitoring (in months)
1	Maragos 1974	Accelerate reef recovery post-disturbance	1. Growth 2. Survival	18
2	Birkeland et al. 1979	Mitigate coral loss prior to a known disturbance	1. Growth 2. Survival	12
3	Bouchon et al. 1981	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Survival	12
4	Auberson 1982	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Survival	12
5	Alcala et al. 1982	Biological response to transplantation	1. Growth 2. Survival 3. Health parameters	12
6	Plucer-Rosario & Randall 1987	Reduce population declines and ecosystem degradation/ Biological response to transplantation	1. Growth 2. Survival	12
7	Guzman 1991	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Survival	36
8	Yap et al. 1992	Re-establishment of a self-sustaining, functioning reef ecosystem/ Biological response to transplantation	1. Growth 2. Survival	60
9	Clark & Edwards 1995	Increase reef recovery post-disturbance	1. Growth 2. Survival 3. Recruitment	28

10	Van Treeck & Schuhmacher 1997	Increase reef recovery post-disturbance/ Biological response to transplantation	1. Survival	12
11	Bowden-Kerby 1997	Biological response to transplantation	1. Growth 2. Survival	3
12	Clark 1997	Biological response to transplantation	1. % tissue regeneration	4
13	Custodio & Yap 1997	Biological response to transplantation	1. Growth	14
14	Yap et al. 1998	Biological response to transplantation	1. Growth 2. Survival 3. Environmental parameters	16
15	Thornton et al. 2000	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Growth 2. Survival	24
16	Bruckner & Bruckner 2000	Reduce population declines and ecosystem degradation	1. Survival 2. Fusion to substrate 3. Strength of attachment 4. Health parameters	24
17	Jaap 2000	Accelerate reef recovery post-disturbance	1. Survival 2. Health parameters 3. Recruitment	24
18	Lam 2000	Biological response to transplantation	1. Growth 2. Survival	12
19	Nagelkerken et al. 2000	Biological response to transplantation	1. Growth 2. Survival	4
20	Rinkevich 2000	Biological response to transplantation	1. Growth 2. Survival	12
21	Ammar et al. 2000	Biological response to transplantation	1. Growth 2. Survival	12
22	Heeger & Sotto 2000	Biological response to transplantation/ Alternative livelihood opportunities	1. Survival	n/a
23	Chabanet & Naim 2001	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Growth 2. Survival	12

24	Raymundo 2001	Biological response to transplantation	1. Growth 2. Health parameters	12
25	Gleason et al. 2001	Biological response to transplantation	1. Growth 2. Survival 3. Reproductive potential	21
26	Bowden-Kerby 2001	Biological response to transplantation	1. Growth 2. Survival 3. Fusion to substrate	12
27	Becker & Mueller 2001	Biological response to transplantation	1. Growth 2. Survival 3. Health parameters	18
28	Salvat et al. 2002	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Growth 2. Survival 3. Health parameters 4. Recruitment	32
29	Yap & Molina 2003	Biological response to transplantation	1. Growth 2. Survival 3. Environmental parameters	18
30	Lindhal 2003	Biological response to transplantation	1. Growth 2. Survival	12
31	Okubo & Motokawa 2003	Biological response to transplantation	1. Reproductive potential	n/a
32	Chilcoat 2004	Biological response to transplantation	1. Growth 2. Survival	24
33	Raymundo & Maypa 2004	Biological response to transplantation	1. Growth 2. Survival 3. Fusion to substrate	12
34	Yap 2004	Biological response to transplantation	1. Survival	3.5
35	Okubo et al. 2005	Biological response to transplantation	1. Growth 2. Survival 3. Reproductive potential	18

36	Morancy et al. 2005	Mitigate coral loss prior to a known disturbance	1. Growth 2. Survival 3. Fish and invertebrates	12
37	Job et al. 2006	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Survival 2. Fish and invertebrates	9
38	Job 2006	Mitigate coral loss prior to a known disturbance	1. Survival 2. Coral cover 3. Fish and invertebrates	9
39	Yeemin 2006	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Growth 2. Survival 3. Fish	108
40	Monty et al. 2006	Biological response to transplantation	1. Survival	19
41	Dizon & Yap 2006	Biological response to transplantation	1. Growth 2. Survival	15
42	Garrison & Ward 2008	Biological response to transplantation	1. Growth 2. Survival	60
43	Cabaitan et al. 2008	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Fish and invertebrates	11

44	Dizon et al. 2008	Biological response to transplantation	1. Survival 2. Fusion to substrate	5
45	Seguin et al. 2008	Mitigate coral loss prior to a known disturbance	1. Survival 2. Growth 3. Health parameters	12
46	Kilbane et al. 2008	Mitigate coral loss prior to a known disturbance	1. Survival 2. Health parameters	12
47	Yap 2009	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Fish and invertebrates	12
48	Perkol-Finkel & Benayahu 2009	Biological response to transplantation	1. Survival	1
49	Palomar et al. 2009	Biological response to transplantation	1. Survival	36
50	Forrester et al. 2010	Biological response to transplantation	1. Growth 2. Survival	48
51	Shaish et al. 2010a	Biological response to transplantation	1. Survival 2. Growth 3. Health parameters	12
52	Shaish et al. 2010b	Biological response to transplantation	1. Growth 2. Survival	15
53	Baria et al. 2010	Biological response to transplantation	1. Survival 2. Algae biomass	3
54	Ferse 2010	Biological response to transplantation	1. Survival	20
55	Miyazaki et al. 2010	Biological response to transplantation	1. Growth 2. Survival	36
56	Williams & Miller 2010	Reduce population declines and ecosystem degradation/ Biological response to transplantation	1. Fusion to substrate 2. Health parameters	12
57	Guest et al. 2011	Biological response to transplantation	1. Time until self-attachment of transplants to substrata	7
58	Gomez et al. 2011	Biological response to transplantation	1. Growth 2. Survival	21

59	Nakamura et al. 2011	Biological response to transplantation	1. Growth	22
60	Linan-Cabello et al. 2011	Biological response to transplantation	1. Survival 2. Growth 3. Health parameters	10
61	Suzuki et al. 2011	Biological response to transplantation	1. Survival	6
62	Horoszowski-Fridman et al. 2011	Biological response to transplantation	1. Reproductive output	48
63	Forrester et al. 2012	Biological response to transplantation	1. Growth 2. Health parameters	24
64	Boch & Morse 2012	Biological response to transplantation	1. Growth 2. Survival	12
65	Garrison & Ward 2012	Reduce population declines and ecosystem degradation	1. Survival	144
66	Ferse et al. 2013	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Survival 2. Recruitment	24
67	Ngai et al. 2013	Increase reef recovery post-disturbance	1. Growth 2. Survival	24
68	Mbije et al. 2013	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Growth 2. Survival 3. Fish and invertebrates 4. Health parameters 5. Recruitment	12
69	Forrester et al. 2013	Biological response to transplantation	1. Growth	36
70	Guest et al. 2014	Biological response to transplantation	1. Growth 2. Survival	30
71	De la Cruz et al. 2014	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Survival 2. Coral cover 3. Fish and invertebrates	19
72	Romatski 2014	Biological response to transplantation	1. Growth 2. Survival	9
73	Toh et al. 2014	Biological response to transplantation	1. Growth 2. Survival	6

74	Forrester et al. 2014	Biological response to transplantation	1. Growth 2. Survival	84
75	Tortolero-langarica et al. 2014	Accelerate reef recovery post-disturbance	1. Growth 2. Survival 3. Fusion to substrate	12
76	Cabaitan et al. 2015	Biological response to transplantation	1. Growth 2. Survival 3. Fusion to substrate	12
77	Ng et al. 2015	Biological response to transplantation	1. Survival	24
78	De la Cruz et al. 2015	Biological response to transplantation	1. Growth 2. Survival	12
79	Horoszowski-Fridman et al. 2015	Reduce population declines and ecosystem degradation	1. Growth 2. Survival 3. Health parameters	17
80	Mercado-Molina et al. 2015	Reduce population declines and ecosystem degradation	1. Growth 2. Survival	12
81	Kotb 2016	Mitigate coral loss prior to a known disturbance	1. Growth 2. Survival	24
82	Miller et al. 2016	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Coral cover	120
83	Montoya-Maya et al. 2016	Re-establishment of a self-sustaining, functioning reef ecosystem	1. Coral cover 2. Recruitment	24

APPENDIX S3

Statistical table for Chapter 3

Table S3.1 Hard coral cover among treatments Posthoc with Tukeys' contrast on linear models

	Estimate	SE	t-value	p-value	
Koh Tao	*LM: ~Treatment+Site*				
restored-control	-9.464	10.153	-0.932	0.6204	
unrestored-control	-42.036	10.153	-4.14	0.0013	**
unrestored-restored	-32.572	6.421	-5.072	0.0002	***
Landaa Giraavaru	*LM: ~Treatment+Site*				
restored-control	5.017	8.381	0.599	0.8187	
unrestored-control	-19.517	8.381	-2.329	0.0719	
unrestored-restored	-24.533	5.301	-4.628	<0.001	***
Florida Keys	GLM: *log(x+1)~Treatment+Site*				
restored-control	1.8037	0.5118	3.524	0.0055	**
unrestored-control	0.6422	0.5118	1.255	0.4288	
unrestored-restored	-1.1615	0.3237	-3.588	0.0049	**
St Croix	GLM: *log(x+1)~Treatment+Site*				
restored-control	0.1896	0.3088	0.614	0.811	
unrestored-control	-0.0692	0.2888	-0.24	0.968	
unrestored-restored	-0.2588	0.1891	-1.369	0.375	

Table S3.2 Structural complexity among treatments. Posthoc with Tukeys' contrast on linear models

	Estimate	SE	t-value	p-value	
Koh Tao	*LM: ~Treatment+Site*				
restored-control	1.25	0.3005	4.16	0.0013	**
unrestored-control	-0.4167	0.3005	-1.387	0.3529	
unrestored-restored	-1.6667	0.19	-8.771	<1e-04	***
Landaa Giraavaru	*LM: log(x+1)~Treatment+Site*				
restored-control	-0.2657	0.1565	-1.697	0.2249	
unrestored-control	-0.6721	0.1565	-4.293	<0.001	***
unrestored-restored	-0.4064	0.099	-4.105	0.0014	**
Florida Keys	*LM: ~Treatment+Site*				
restored-control	-0.3333	0.2679	-1.244	0.4346	
unrestored-control	-0.8333	0.2679	-3.111	0.014	*
unrestored-restored	-0.5	0.1694	-2.951	0.0198	*
St Croix	*LM: ~Treatment+Site*				
restored-control	0.075	0.2077	0.361	0.9291	
unrestored-control	-0.7875	0.1943	-4.054	0.0031	**
unrestored-restored	-0.8625	0.1272	-6.782	<0.001	***

Table S3.3 Coral juveniles among treatment. Posthoc on Kruskal Wallis with Nemenyi test

Koh Tao	*Kruskal-Wallis: Nemenyi test*	
	control	restored
restored	0.452	NA
unrestored	0.452	0.043
Landaa Giraavaru	*Kruskal-Wallis: Nemenyi test*	
	control	restored
restored	0.64	NA
unrestored	0.9	0.88

Table S3.4 Coral juveniles among restored sites in Koh Tao. Posthoc on Kruskal Wallis with Nemenyi test

Koh Tao	*Kruskal-Wallis: Nemenyi test*	
	Biorock	Chalok
Chalok	0.822	NA
Tanote	0.2	0.05*

Table S3.5 Coral generic richness among treatments. Posthoc with Tukeys' contrast on general linear models and Kruskal Wallis with Nemenyi test

	Estimate	**SE**	**t-value**	**p-value**	
Koh Tao	*GLM: ~Treatment+Site* Distribution= poisson				
restored-control	5.667	2.557	2.216	0.0896	
unrestored-control	1.333	2.557	0.521	0.8588	
unrestored-restored	-4.333	1.617	-2.68	0.0352	*
Landaa Giraavaru	*GLM: ~Treatment+Site* Distribution= poisson				
restored-control	-36.5	4.902	-7.446	<0.001	***
unrestored-control	-23.833	4.902	-4.862	<0.001	***
unrestored-restored	12.667	3.1	4.086	0.0015	**
Florida Keys	*GLM: ~Treatment+Site* Distribution= poisson				
restored-control	0.2222	0.7349	0.302	0.9498	
unrestored-control	-0.8889	0.7349	-1.209	0.4542	
unrestored-restored	-1.1111	0.4648	-2.39	0.0639	
St Croix	*Kruskal-Wallis: Nemenyi test*				
	control	restored			
restored	1	NA			
control	0.74	0.77			

Table S.3.6 Coral health prevalence among treatments. Posthoc with Tukeys' contrast on general linear models

	Estimate	**SE**	**t-value**	**p-value**	
Koh Tao	*GLM: ~Treatment+Site*				
restored-control	5.499	6.529	0.842	0.6759	
unrestored-control	-24.433	6.529	-3.742	0.0033	**
unrestored-restored	-29.932	4.129	-7.249	<1e-04	***

Landaa Giraavaru	*GLM: ~Treatment+Site*				
restored-control	-9.1227	1.7434	-5.233	<0.001	***
unrestored-control	-8.9282	1.7434	-5.121	<0.001	***
unrestored-restored	0.1945	1.1026	0.176	0.9826	
Florida Keys	*GLM: ~Treatment+Site*				
restored-control	-1.897	2.594	-0.731	0.7431	
unrestored-control	2.08	2.594	0.802	0.7005	
unrestored-restored	3.976	1.64	2.424	0.0596	
St Croix	*GLM: ~Treatment+Site*				
restored-control	-15.34	2.217	-6.919	<0.001	***
unrestored-control	-12.224	2.074	-5.894	<0.001	***
unrestored-restored	3.116	1.358	2.295	0.0863	

Table S.3.7 Coral disease prevalence among treatments. Posthoc with Tukeys' contrast on general linear models

	Estimate	SE	t-value	p-value	
Koh Tao	*GLM: log(x+1)~Treatment+Site*				
restored-control	0.7201	0.5733	1.256	0.428	
unrestored-control	0.9191	0.5733	1.603	0.261	
unrestored-restored	0.199	0.3626	0.549	0.845	
Landaa Giraavaru	*GLM: log(x+1)~Treatment+Site*				
restored-control	1.1601	0.4092	2.835	0.0253	*
unrestored-control	0.7145	0.4092	1.746	0.2075	
unrestored-restored	-0.4456	0.2588	-1.722	0.2159	
Florida Keys	*GLM: log(x+1)~Treatment+Site*				
restored-control	-0.5942	0.2137	-2.781	0.0284	*
unrestored-control	-0.7363	0.2137	-3.446	0.0065	**
unrestored-restored	-0.1421	0.1351	-1.051	0.5473	
St Croix	*GLM: log(x+1)~Treatment+Site*				
restored-control	0.4209	0.1529	2.752	0.0373	*
unrestored-control	-0.0533	0.1431	-0.372	0.9249	
unrestored-restored	-0.4742	0.0937	-5.063	<0.001	***

Table S3.8 Prevalence of compromised coral colonies among treatments. Posthoc with Tukeys' contrast on general linear models

	Estimate	SE	t-value	p-value	
Koh Tao	*GLM: log(x+1)~Treatment+Site*				
restored-control	-0.7677	0.3477	-2.208	0.0909	
unrestored-control	0.748	0.3477	2.151	0.1012	
unrestored-restored	1.5157	0.2199	6.893	<1e-04	***
Landaa Giraavaru	*GLM: log(x+1)~Treatment+Site*				
restored-control	0.6767	0.6425	1.053	0.546	
unrestored-control	0.2779	0.6425	0.433	0.9	
unrestored-restored	-0.3988	0.4064	-0.981	0.59	

Florida Keys	*GLM: log(x+1)~Treatment+Site*				
restored-control	0.2032	0.402	0.505	0.867	
unrestored-control	-0.3443	0.402	-0.856	0.667	
unrestored-restored	-0.5475	0.2543	-2.153	0.101	
St Croix	*GLM: log(x+1)~Treatment+Site*				
restored-control	1.8198	0.2296	7.928	<1e-04	***
unrestored-control	1.5144	0.2147	7.053	<1e-04	***
unrestored-restored	-0.3054	0.1406	-2.173	0.107	

Table S3.9 Prevalence of predated upon coral colonies among treatments. Posthoc with Tukeys' contrast on general linear models, and Kruskal Wallis Nemenyi tests

	Estimate	SE	t-value	p-value
Koh Tao	*GLM: ~Treatment+Site* Distribution= poisson			
restored-control	-0.0954	0.4061	-0.235	0.969
unrestored-control	-0.0577	0.4061	-0.142	0.989
unrestored-restored	0.0377	0.2568	0.147	0.988
Landaa Giraavaru	*Kruskal-Wallis: Nemenyi test*			
	control	restored		
restored	0.36	NA		
control	0.34	1		
Florida Keys	*Kruskal-Wallis: Nemenyi test*			
	control	restored		
restored	0.0038*	NA		
control	1	0.0038*		
St Croix	*Kruskal-Wallis: Nemenyi test*			
	control	restored		
restored	0.56	NA		
control	0.92	0.33		

Table S3.10 Pairwise ADONIS investigating the compositional differences in coral assemblages among restoration treatments at the four program locations calculated from Bray-Curtis distance matrices. * indicates significant effect at p < 0.05. ** at p < 0.01 and *** at p < 0.005

	F model	r^2	p-value	
Koh Tao				
unrestored versus restored	1.4111	0.081	0.231	
unrestored versus control	4.5256	0.2204	0.008	**
restored versus control	3.6418	0.1854	0.014	*
Landaa Giraavaru				
unrestored versus restored	3.3293	0.1722	0.015	**
unrestored versus control	2.2932	0.1253	0.045	*
restored versus control	3.7858	0.1913	0.005	**
Florida Keys				
unrestored versus restored	3.5209	0.1803	0.014	*

unrestored versus control	3.8769	0.195	0.006	**
restored versus control	1.3553	0.078	0.261	
St Croix				
unrestored versus restored	6.9563	0.3669	0.001	**
unrestored versus control	3.1466	0.2077	0.017	*
restored versus control	3.5079	0.2262	0.004	**

APPENDIX S4

Statistical tables for Chapter 4

Table S4.1 Pairwise comparisons from Tukeys' contrasts on GLM of total fish counts among treatments at the four locations

	Estimate	SE	z value	p-value
Koh Tao - Thailand	*GLM: ~Treatment+Site family= negative binomial*			
restored-control	-0.4434	0.4642	-0.955	0.605
unrestored-control	-0.2849	0.4644	-0.613	0.813
unrestored-restored	-0.7283	0.4643	-1.568	0.259
Landaa Giraavaru - Maldives	*GLM: ~Treatment+Site family= negative binomial*			
restored-control	-0.3592	0.5634	-0.638	0.799
unrestored-control	0.1413	0.5634	-0.251	0.966
unrestored-restored	0.2179	0.5634	0.387	0.921
Florida Keys - USA	GLM: ~Treatment+Site family= negative binomial			
restored-control	-0.5111	0.3421	-1.494	0.294
unrestored-control	-0.0387	0.3412	-0.114	0.993
unrestored-restored	0.4724	0.3421	1.381	0.351
St Croix – US Virgin Islands	GLM: ~Treatment+Site family= negative binomial			
restored-control	-0.3809	0.4606	-0.827	0.686
unrestored-control	-0.5576	0.4608	-1.21	0.447
unrestored-restored	-0.1767	0.4611	-0.383	0.922

Table S4.2 Pairwise comparisons from Tukeys' contrasts on GLM of total fish counts among sites at the four locations. * indicates significant effect at $p < 0.05$. ** at $p < 0.01$ and *** at $p < 0.005$

	Estimate	SE	z value	p-value
Koh Tao - Thailand	*GLM: ~Treatment+Site family= negative binomial*			
Chalok-Biorock	-0.0829	0.5709	-0.145	1
Green rock-Biorock	-0.7805	0.6997	-1.115	0.873
Shark island- Biorock	-0.0213	0.6992	-0.03	1
Tanote-Biorock	-0.4053	0.5711	-0.71	0.98
Tao Tong-Biorock	-0.2196	0.6993	-0.314	1
Green rock- Chalok	-0.6976	0.6998	-0.997	0.917
Shark island-Chalok	0.0616	0.6993	0.088	1
Tanote-Chalok	-0.3224	0.5711	-0.565	0.993
Tao Tong-Chalok	-0.1367	0.6994	-0.195	1
Shark island-Green rock	0.7592	0.8078	0.94	0.935
Tanote-Green rock	0.3752	0.6998	0.536	0.995
Tao Tong-Green rock	0.5609	0.8079	0.694	0.982
Tanote- Shark island	-0.384	0.6994	-0.549	0.994
Tao Tong- Shark island	-0.1983	0.8075	-0.246	1

Tao Tong- Tanote	0.1857	0.6994	0.265	1	
Landaa Giraavaru - Maldives	*GLM: ~Treatment+Site family= negative binomial*				
H2-H1	-1.155	0.9536	-1.211	0.829	
H3-H1	-0.9431	0.9535	-0.989	0.92	
LG1-H1	-0.5038	0.8255	-0.61	0.99	
LG2-H1	-0.6218	0.8256	-0.753	0.974	
LG3-H1	-1.6412	0.826	-1.987	0.345	
H3-H2	0.2119	0.9539	0.222	1	
LG1-H2	0.6512	0.8261	0.788	0.969	
LG2-H2	0.5332	0.8361	0.645	0.987	
LG3-H2	-0.4862	0.8265	-0.588	0.992	
LG1-H3	0.4393	0.8259	0.532	0.995	
LG2-H3	0.3213	0.8259	0.389	0.999	
LG3-H3	-0.6981	0.8263	-0.845	0.958	
LG2-LG1	-0.118	0.6742	-0.175	1	
LG3-LG1	-1.1374	0.6747	-1.686	0.536	
LG3-LG2	-1.0194	0.6747	-1.511	0.652	
Florida Keys - USA	GLM: ~Treatment+Site family= negative binomial				
CNC- Carysfort	-0.631	0.4669	-1.352	0.7518	
Horseshoe-Carysfort	-0.4368	0.4952	-0.936	0.9349	
Molasses-Carysfort	1.3401	0.4586	2.922	0.0366	*
Pickles-Carysfort	-0.113	0.3779	-0.299	0.9997	
White bank-Carysfort	0.6979	0.3759	1.856	0.4239	
Horseshoe-CNC	0.1942	0.5402	0.359	0.9992	
Molasses-CNC	1.9711	0.5345	3.688	0.003	**
Pickles-CNC	0.5179	0.4672	1.109	0.8755	
White bank-CNC	1.3289	0.4656	2.854	0.0481	*
Molasses-Horseshoe	1.7769	0.5331	3.334	0.01081	*
Pickles-Horseshoe	0.3238	0.4655	0.696	0.982	
White bank-Horseshoe	1.1347	0.4639	2.446	0.1378	
Pickles-Molasses	-1.4532	0.4589	-3.167	0.0186	*
White bank-Molasses	-0.6422	0.4573	-1.405	0.7199	
White bank-Pickles	0.8109	0.3763	2.155	0.2548	
St Croix – US Virgin Islands	GLM: ~Treatment+Site family= negative binomial				
Cane Bay H-Cane Bay	0.9157	0.6366	1.438	0.703	
Green Cay-Cane Bay	-0.44	0.6385	-0.689	0.983	
Knights Bay-Cane Bay	0.1707	0.6373	0.268	1	
Knights Bay H-Cane Bay	-0.2626	0.6822	-0.385	0.999	
Pavillions-Cane Bay	0.536	0.6808	0.787	0.97	
Green Cay-Cane Bay H	-1.3558	0.5902	-2.297	0.194	
Knights Bay-Cane Bay H	-0.745	0.589	-1.265	0.804	
Knights Bay H-Cane Bay H	-1.1784	0.6373	-1.849	0.433	
Pavillions-Cane Bay H	-0.3797	0.6357	-0.597	0.991	

Knights Bay-Green Cay	0.6107	0.591	1.033	0.906
Knights Bay H-Green Cay	0.1774	0.6391	0.278	1
Pavillions-Green Cay	0.9761	0.6376	1.531	0.643
Knights Bay H-Knights Bay	-0.4333	0.638	-0.679	0.984
Pavillions-Knights Bay	0.3653	0.6365	0.574	0.993
Pavillions-Knights Bay H	0.7987	0.6814	1.172	0.85

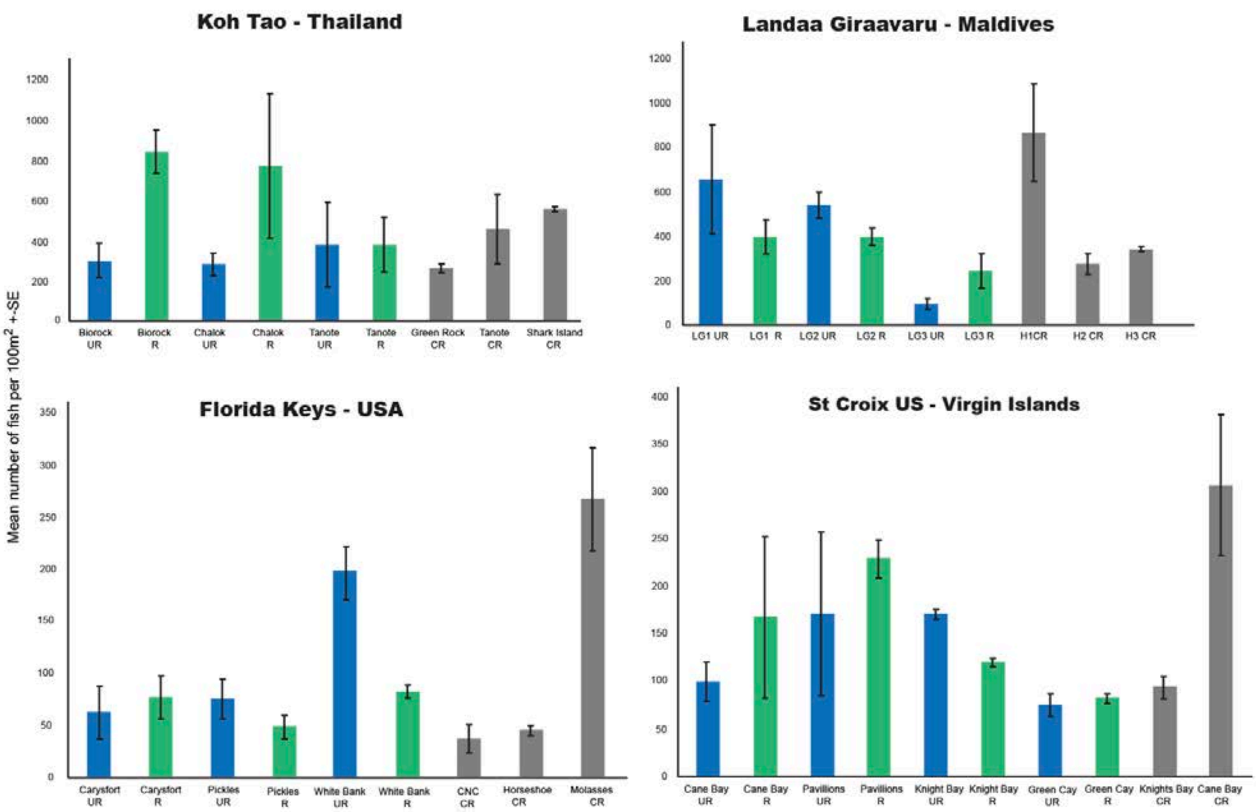

Figure S4.1 Mean fish abundance per 100m^2 transects (±SE) by sites at each of the four restoration programs

Table S4.3 Pairwise comparisons from Tukeys' contrasts on GLM of total fish counts per size classes (small, medium, and large) among treatments at the four locations. * indicates significant effect at p < 0.05. ** at p < 0.01 and *** at p < 0.005

	Estimate	SE	z value	p-value	
Koh Tao - Thailand	*GLM: ~Treatment+Site family= negative binomial*				
Small					
restored-control	-0.4856	0.2582	-1.88	0.1443	
unrestored-control	-0.8762	0.2585	-3.3	0.0019	**
unrestored-restored	-0.3906	0.2587	-1.51	0.2862	
Medium					
restored-control	0.4413	0.4243	1.04	0.5516	
unrestored-control	1.1344	0.4213	2.692	0.0193	*
unrestored-restored	0.6931	0.418	1.658	0.2215	

Large					
restored-control	0.7309	0.5527	1.322	0.383	
unrestored-control	0.869	0.5505	1.579	0.255	
unrestored-restored	0.1382	0.5321	0.26	0.964	
Landaa Giraavaru - Maldives	*GLM: ~Treatment+Site family= negative binomial*				
Small					
restored-control	-0.3852	0.2946	-1.308	0.391	
unrestored-control	-0.2344	0.2945	-0.796	0.706	
unrestored-restored	0.1508	0.2947	0.512	0.866	
Medium					
restored-control	0.2898	0.4267	0.679	0.7757	
unrestored-control	1.28	0.4221	3.033	0.0069	**
unrestored-restored	0.9902	0.4196	2.36	0.0481	*
Large					
restored-control	0.4055	0.9129	0.444	0.895	
unrestored-control	1.7047	0.7687	2.218	0.066	
unrestored-restored	1.2993	0.6513	1.995	0.11	
Florida Keys - USA	*GLM: ~Treatment+Site family= negative binomial*				
Small					
restored-control	0.005	0.4709	0.016	1	
unrestored-control	0.2043	0.4685	0.655	0.789	
unrestored-restored	0.669	0.471	0.639	0.799	
Medium					
restored-control	-0.7023	0.4709	-1.491	0.295	
unrestored-control	-0.0323	0.4685	-0.069	0.997	
unrestored-restored	0.6699	0.471	-1.422	0.329	
Large					
restored-control	-2.7316	0.7339	-3.722	0.0006	***
unrestored-control	-0.7755	0.6909	-1.122	0.4999	
unrestored-restored	1.9561	0.7376	2.652	0.0216	*
St Croix – US Virgin Islands	*GLM: ~Treatment+Site family= negative binomial*				
Small					
restored-control	-0.5845	0.2661	-2.197	0.0717	
unrestored-control	-0.7818	0.2666	-2.932	0.0096	**
unrestored-restored	-0.1973	0.2677	0.737	0.7415	
Medium					
restored-control	1.0202	0.4265	2.392	0.0443	*
unrestored-control	0.919	0.4272	2.111	0.0875	
unrestored-restored	-0.1183	0.4182	-0.283	0.9568	
Large					
restored-control	0.31845	0.3286	-0.969	0.596	

unrestored-control	-0.383	0.3348	-1.144	0.487
unrestored-restored	-0.0645	0.3594	-0.18	0.982

Table S4.4 Pairwise ADONIS investigating the compositional differences in fish communities among restoration treatments at the four program locations calculated from Bray-Curtis distance matrices. * indicates significant effect at $p < 0.05$. ** at $p < 0.01$ and *** at $p < 0.005$

	F model	r^2	p-value	
Koh Tao - Thailand				
unrestored versus restored	1.0842	0.0634	0.344	
unrestored versus control	3.0593	0.1605	0.014	*
restored versus control	1.479	0.0846	0.173	
Landaa Giraavaru - Maldives				
unrestored versus restored	0.4775	0.0289	0.835	
unrestored versus control	0.7831	0.0466	0.588	
restored versus control	1.1	0.0641	0.346	
Florida Keys - USA				
unrestored versus restored	0.8694	0.0515	0.462	
unrestored versus control	1.7657	0.0993	0.125	
restored versus control	0.8314	0.0493	0.595	
St Croix – US Virgin Islands				
unrestored versus restored	0.5327	0.0425	0.783	
unrestored versus control	1.03	0.079	0.355	
restored versus control	0.7599	0.0595	0.488	

Table S4.5 ADONIS test results on the effect of benthic variables on the fish assemblage composition at the four program locations based on Bray-Curtis distance matrices. n=999 permutations. * indicates significant effect at $p < 0.05$. ** at $p < 0.01$ and *** at $p < 0.005$

	df	Sums of squares	F model	r^2	p-value	
Koh Tao - Thailand						
Hard coral cover	1	0.2401	2.7345	0.0899	0.018	*
Structural complexity	1	0.2836	3.229	0.1061	0.014	*
Acroporids	1	0.0955	1.0871	0.0357	0.363	
Branching	1	0.1137	1.2959	0.0426	0.275	
Diversity	1	0.095	1.082	0.0356	0.411	
Landaa Giraavaru - Maldives						
Hard coral cover	1	0.0848	0.9697	0.0291	0.44	
Structural complexity	1	0.142	1.6249	0.0488	0.122	
Acroporids	1	0.5257	6.0141	0.1808	0.001	***
Branching	1	0.1139	1.3032	0.0392	0.227	
Diversity	1	0.2059	2.3551	0.0708	0.041	*
Florida Keys - USA						
Hard coral cover	1	0.0896	0.8967	0.0325	0.471	

Structural complexity	1	0.2615	2.6162	0.0949	0.033	*
Acroporids	1	0.1214	1.2151	0.0441	0.288	
Gorgonians	1	0.0173	0.1731	0.0063	0.98	
Diversity	1	0.1642	1.6427	0.0596	0.154	
St Croix – US Virgin Islands						
Hard coral cover	1	0.5175	7.1323	0.1706	0.001	***
Structural complexity	1	0.0889	1.2262	0.0293	0.285	
Acroporids	1	0.2283	3.147	0.0753	0.022	*
Gorgonians	1	0.6651	9.1658	0.2193	0.001	***
Diversity	1	0.445	6.13	0.1466	0.002	**

Table S4.6 ADONIS test results on the effect of sites on the fish assemblage composition at the four program locations based on Bray-Curtis distance matrices. n=999 permutations. * indicates significant effect at $p < 0.05$. ** at $p < 0.01$ and *** at $p < 0.005$

	df	Sums of squares	F model	r^2	p-value	
Koh Tao - Thailand						
Site	5	0.8932	2.109	0.33428	0.002	**
Residuals	21	1.7788	0.6657			
Landaa Giraavaru - Maldives						
Site	5	1.4065	3.9342	0.4837	0.001	***
Residuals	21	1.5015	0.5163			
Florida Keys - USA						
Site	5	0.9867	2.3463	0.3584	0.003	**
Residuals	21	1.7662	0.6416			
St Croix – US Virgin Islands						
Site	5	1.9563	5.4502	0.6449	0.001	***
Residuals	15	1.0768	0.355			

Table S4.7 ADONIS test results on the effect of restoration treatment on the fish assemblage composition of classes small, medium, and large at the four program locations based on Bray-Curtis distance matrices. n= 999 permutations. * indicates significant effect at $p < 0.05$. ** at $p < 0.01$ and *** at $p < 0.005$

	df	Sums of squares	F model	r^2	p-value	
Koh Tao - Thailand						
Small						
Treatment	2	0.4181	2.4035	0.1669	0.01	**
Residuals	24	2.0874	0.8331			
Medium						
Treatment	2	0.7258	1.7052	0.1244	0.077	
Residuals	24	5.1078	0.8756			
Large						

Treatment	2	0.1947	0.3387	0.0344	0.946	
Residuals	19	5.46	0.9656			
Landaa Giraavaru - Maldives						
Small						
Treatment	2	0.1665	0.8105	0.0633	0.637	
Residuals	24	2.4644	0.9367			
Medium						
Treatment	2	0.3065	0.6626	0.0523	0.797	
Residuals	24	5.5499	0.9477			
Large						
Treatment	2	1.0399	1.3362	0.2763	0.201	
Residuals	7	2.724	0.7237			
Florida Keys - USA						
Small						
Treatment	2	0.2007	0.9972	0.0767	0.433	
Residuals	24	2.4152	0.9233			
Medium						
Treatment	2	0.3062	0.7107	0.0582	0.739	
Residuals	23	4.9544	0.9418			
Large						
Treatment	2	1.2758	2.4413	0.2134	0.01	**
Residuals	18	4.7031	0.7866			
St Croix – US Virgin Islands						
Small						
Treatment	2	0.3094	1.008	0.1007	0.418	
Residuals	18	2.7628	0.8993			
Medium						
Treatment	2	0.1663	0.4344	0.046	0.931	
Residuals	18	3.4462	0.9539			
Large						
Treatment	2	0.2408	0.7763	0.0794	0.592	
Residuals	18	2.7921	0.9206			

APPENDIX S5.1

Further description of the methods and respondent demographics

Section 1. Tables

Table S5.1 Details of the four programs surveyed

Project	location	Number of people involved			Age of the project	Objectives of the project	Outreach	Funding
		Staff	Interns	Volunteers				
New Heaven Reef Conservation Program	Koh Tao-Thailand	6	1 to 8	up to 30	10 years (Started 2007)	1. Teach 2. Alleviate diving pressure from natural reefs 3. Assist coral recovery in high diving pressure areas (providing structures for corals that have been damaged)	"Save Koh Tao" group and programs with local schools	Private. Through the New Heaven Reef Conservation Program
Reefscapers	Landaa Giraavaru-Maldives	2 on site and 4 or 5 on an adjacent island	1	1	12 years (Started in 2004-2005)	1. Increase reef complexity, habitat diversity and biodiversity 2. Provide alternative sustainable livelihoods 3. Make the hotel's house reef attractive to raise funds and appeal to the guests 4. Provide guest experience	Hotel guests and local school groups	Private. Through hotel guests buying frames

Coral Restoration Foundation	Florida-United States of America	13	7 to 10	100+	10 years (Started 2007)	1. Grow and restore threatened species of Caribbean corals, with a historical focus and targeted effort on *Acropora* corals 2. Education. Teach about coral reef ecosystems and bring awareness to ocean conservation solutions 3. Science. Develop best science and collaborate to improve restoration techniques	Volunteers and members of the local, national, and international community. Fundraising events	Grants (private, Government, local NGOs) and public outreach
The Nature Conservancy	St Croix-US Virgin Islands	3	2	NA	8 years (Started 2009)	1. Grow and restore threatened species of *Acropora* corals		Grants and TNC

Table S5.2 Demographics of the surveys' respondents

Program	Respondent role	Total	Gender	
			F	M
New Heaven Reef Conservation Program	Project interns	10	5	5
	Dive industry	8	3	5
	Project staff	6	2	4
	Project volunteers	4	2	2
	Local community	2	2	0
Total		**30**	**14**	**16**
Reefscapers	Dive industry	10	4	6
	Project staff	8	4	4
	Tourism industry	8	1	7

	Project interns	2	1	1
	Local community	2	0	2
Total		**30**	**10**	**20**
Coral Restoration Foundation	Project staff	8	6	2
	Dive industry	8	5	3
	Conservation professionals	6	4	2
	Project interns	3	2	1
	Fishermen	3	0	3
	Tourism industry	2	1	1
Total		**30**	**18**	**12**
The Nature Conservancy	Dive industry	12	4	8
	Project staff	6	3	3
	Local community	3	3	0
	Project volunteers	3	1	2
	Conservation professionals	2	2	0
	Project interns	2	1	1
	Fishermen	2	0	2
Total		**30**	**14**	**16**
Grand Total		**120**	**56**	**64**

Section 2. Interview questionnaire

Below is the questionnaire that was used for face to face key-informant interviews at all four locations*. This questionnaire was approved under the Human Ethics permit #H6539 by the Human Ethics Research Committee at James Cook University. The informed consent for that was given to all respondents is available in Section 3.

Thank you for participating in this interview about the relative benefits of coral restoration in location "X". As indicated in the information sheet, the interview will last approximately 30 minutes. Your identity will be kept completely confidential during the analysis and communication of the data obtained from this interview.

Give a brief introduction of myself and my project and explain why their help is so important to my project. Ask the interviewee if he is willing to fill in the informed consent form and be audio-recorded.

**Question 5c' was only administered to respondents in the Florida Keys, and US Virgin Islands.*

1. Tell me a little bit about yourself and your background in relation to the coral restoration project…

1.a. How long have you been in *location X*?

Years:______ Months: ______ Weeks: ______ Days: ______

1.b. Have you spent all that time working on the restoration project?

YES/NO

If no: - What other activities have you been involved in?

- How much time have you dedicated to the restoration project?

Years:______ Months: ______ Weeks: ______ Days: ______

1.c. Did you have any prior experience with coral restoration?

YES/NO

If yes: Where was this? Could you describe your experience to me?

1.d. At what level would you rate your coral reef knowledge?

Basic 1__2__3__4__5__6__7__8__9__10 very advanced

To project managers:

1.e. Can you tell me more about the restoration project?

Prompts:
- When was it started?
- How is the project funded?
- Are there any key events about the restorations effort that you recall (e.g. bleaching event, storm, massive transplantation effort?)

To other businesses/members of local community

1.f. Can you tell me more about your business?

Prompts:

- When was it started?
- How does it relate to the restoration effort?

2. Tell me more about your diving/snorkelling experience

2.a. Do you scuba dive?

YES/NO

If yes: Approximately how many dives have you done in your life?

1. [10-20]   2. [20-100]   3. [100+]

2.b. Do you snorkel?

YES/NO

If yes: Approximately how many snorkel dives have you done in your life?

1. [10-20]   2. [20-100]   3. [100+]

2.c. Have you visited many other reef regions than *location X*?

YES/NO

If yes: Tick as many as apply:

☐ Red Sea ☐ South Pacific ☐ Other Pacific ☐ Caribbean
☐ South-East Asia ☐ Other Indian Ocean ☐ Other____________

2.d. What do you think the reefs around *location X* looks like? Could you rate the reefs on a scale from 1 to 10 for the following:

> Beauty:

Explain what I mean by beauty… a qualitative assessment of the "wow factor associated with their experience:

2.d.1. Beauty

Not at all beautiful 1__2__3__4__5__6__7__8__9__10 Most beautiful reefs I have ever dived

> Abundance of marine life:

Explain what I mean by abundance… the quantity of things such as schools of fish, very high coral cover

2.d.2. Coral:

Not at all abundant 1__2__3__4__5__6__7__8__9__10 Extremely abundant

2.d.3. Fish:

Not at all abundant 1__2__3__4__5__6__7__8__9__10 Extremely abundant

Explain what I mean by other organisms: everything else such as invertebrates (urchins, nudibranchs, sea stars, etc…), turtles, etc…

2.d.4. Other organisms:

Not at all abundant 1__2__3__4__5__6__7__8__9__10 Extremely abundant

> Diversity of marine life

2.d.5. Coral:

Not at all diverse 1__2__3__4__5__6__7__8__9__10 Extremely diverse

2.d.6. Fish:

Not at all diverse 1__2__3__4__5__6__7__8__9__10 Extremely diverse

2.d.7. Other organisms:

Not at all diverse 1__2__3__4__5__6__7__8__9__10 Extremely diverse

3. Tell me what you think about the restoration program

3.a. What are the 3 best things about the program?

-
-
-

Prompts: Lead respondents to focus their answers towards outcomes

3.b. What are the 3 greatest problems about the program?

-
-
-

3.c. Could you rate the restored reefs on a scale from 1 to 10 for the following:

>Beauty:

3.c.1. Beauty

Not at all beautiful 1__2__3__4__5__6__7__8__9__10 Most beautiful reefs I have ever dived

> Abundance of marine life:

3.c.2. Coral:

Not at all abundant 1__2__3__4__5__6__7__8__9__10 Extremely abundant

3.c.3. Fish:

Not at all abundant 1__2__3__4__5__6__7__8__9__10 Extremely abundant

3.c.4. Other organisms:

Not at all abundant 1__2__3__4__5__6__7__8__9__10 Extremely abundant

> Diversity of marine life

3.c.5. Coral:

Not at all diverse at all 1__2__3__4__5__6__7__8__9__10 Extremely diverse

3.c.6. Fish:

Not at all diverse 1__2__3__4__5__6__7__8__9__10 Extremely diverse

3.c.7. Other organisms:

Not at all diverse 1__2__3__4__5__6__7__8__9__10 Extremely diverse

4. Financial contributions

To tourists/volunteers:

4.a. Can I ask if you have financially contributed to the restoration project?

YES/NO

If yes: How much have you donated?

< US$100 US$100- US$1000 >US$1000

4.b. Are you happy about this? Do you think that you have got value from this contribution?

YES/NO

To project managers:

4.c. Do you think the restoration program provides any economic benefits?

Prompts
- To whom?
- What about to you personally?
- What about the local community?

4.d. How many people are employed for restoration efforts?

Prompts:
- How many are members of the local community?
- How many are foreigners? Where are they from?

4.e. How much do they make approximately? Could you give me a range of the wages?

4.f. Do you think the restoration project benefits other businesses in *location X*?

YES/NO

If yes: What other businesses (e.g, clinics, restaurants, hotels etc…)?

4.g. Do you think the number of tourists/visitors has changed since the restoration efforts started?

YES/NO

If yes: How would you categorise the change:

A lot less ___ Less ___ Same ___ More ___ A lot more ___ I don't know

4.h. Has your business benefited from the restoration efforts around the island

YES/NO

If yes: In what capacity?

4. i. Is there added value for your business in visiting restored areas?

YES/NO

If yes: In what capacity?

5. Overall opinion on the success of the restoration project

5.a. How important do you think the restoration efforts are for the reefs of *location X*?

Prompts

5.a.1. Ecological importance

Explain that ecological importance relates to how the restoration efforts impact the reef in terms corals, fish and other organisms.

Not at all important 1__2__3__4__5__6__7__8__9__10 Very important

5.a.2. Socio- cultural importance

Explain that socio-cultural importance relates to how the restoration efforts affect local stakeholders from tourists to members of the local community in terms of stewardship, increased livelihood opportunities, etc…

Not at all important 1__2__3__4__5__6__7__8__9__10 Very important

5.a.3. Economic importance

Explain that economic relates to how the restoration efforts may provide some economic benefits to local communities/businesses

Not at all important 1__2__3__4__5__6__7__8__9__10 Very important

5.a.4. Governance importance

Explain that governance relates to how the restoration efforts may provide improved capacity building for local communities- may give more weight to protect reefs around location x. Incentive for reef conservation

Not at all important 1__2__3__4__5__6__7__8__9__10 Very important

5.b. Do you see any issue(s) that affect(s) the success of the project?

YES/NO

If yes: What are they? How might these be overcome?

Prompts: Illegal fishing/ water quality/ mass tourism/ climate change

5.c. What do you think the restoration project will look like in 10 years time?

Prompts: Guide towards comparisons with unrestored areas. Also try to focus answers on ecosystem services

5.c'. There is a big debate in the scientific community at the moment- with some scientists highly criticising coral restoration science saying it's worthless in the face of global climate and global impacts, and other scientists saying that we have to do something and we might as well try… What do you think about this?

5.d. How satisfied are you with your involvement in the restoration project?

Very unsatisfied ___ Unsatisfied___ Neutral ___ Satisfied ___ Highly satisfied ___ I Don't know

Prompts: why do you feel this way?

5.e. Would you come to the program again?

YES/NO

Prompts: why?

5.f. Would you recommend the program to others?

YES/NO

Prompts: why?

5.g. Is there anything else you would like to share with me?

Thank you very much for your time. You have given me some valuable insights. Please do not hesitate to contact me if you have any questions or further observations regarding my project.

Section 3. Informed consent form

PRINCIPAL INVESTIGATOR
PROJECT TITLE: Characterising the socio-ecological benefits of coral restoration to develop best-practice guidelines to support reef resilience
INSTITUTION

I understand the aim of this research study is to assess the relative benefits of coral restoration projects. I consent to participate in this project, the details of which have been explained to me, and I have been provided with a written information sheet to keep.

I understand that my participation will involve an interview of approximately 30 minutes, and I agree that the researcher may use the results as described in the information sheet.

I acknowledge that:

- Taking part in this study is voluntary and I am aware that I can stop taking part in it at any time without explanation or prejudice and to withdraw any unprocessed data I have provided;

- That any information I give will be kept strictly confidential and that no names will be used to identify me with this study without my approval;

(Please tick to indicate consent)

I consent to be interviewed	☐	**Yes**	☐	**No**
I consent for the interview to be audio taped	☐	**Yes**	☐	**No**

Name: *(printed)*	
Signature:	**Date:**

APPENDIX S5.2

Summary tables for benefits and limitations of coral restoration

Table S5.3 Summary table of the coding for benefits among responses to the question "What would you say are the three best things about the coral restoration project" at all four case studies. Number of sources refer to number of respondents, while number of references refers to the responses that fit within each themes, sub-themes, and categories. N=116 respondents

Emerging themes	Sub-themes	Categories	# sources	# references	KT sources	LG sources	FK sources	SC sources
Socio-cultural benefits			**84**	**183**	**23**	**19**	**22**	**20**
	Education		39	61	11	12	10	6
			"It's a teaching tool" (SC19DI) "I wasn't educated when I arrived, and I feel I am well educated now." (KT30PI) "The education they give to the people. I went to their classes and it's very educational." (FK06DI)					
		About coral reefs	11	11	5	3	2	1
			"All the students they come here feel like they're taking this environmental message home." (KT15PS) "A lot of people don't know much about corals- including myself, I've learned a lot by working on the restoration project" (LG11PS) "[education]...about why it's necessary to maintain a healthy reef." (SC08PV)					
		About restoration	7	7	3	1	2	1

	"He’s really taught a lot of people how to grow corals, in a very effective way." (FK16CP) "You gain really valuable knowledge about how to do this work anywhere in the world." (KT24PI) "You have to learn quite a few things to do it right. Both the science and the techniques." (KT21PI)					
Awareness	22	23	6	3	7	6
	"It’s brought a lot of public awareness. People are a lot more aware of the problems going on out there" (FK12CP) "It does create a nice community awareness. The locals are starting to understand the needs of protecting the reefs through these projects." (KT23DI) "I think it’s good to make people aware of environmental issues that can affect the ocean." (SC23DI)					
It's happening	16	16	1	4	2	9
	"I think the coolest thing we are doing is actually going out and restoring the reef." (FK18PS) "The fact that there is an effort going in to actually try and restore the reef, which I think is very important" (LG04PS) "The good part is that somebody is actually paying attention and doing it" (SC26DI)					
Stewardship	14	15	5	4	3	2
	"Even if they don’t live by the sea they feel kind of like inspired to do more which I think is super important." (KT15PS) "… try to get them to understand they can do something about the overall stuff, even if it’s small stuff" (LG29PS) "I am going to educate everyone now. If I go to the beach and see something wrong then I can talk to the people and explain what’s going on" (KT30PI)					
Community involvement	11	22	1	3	4	3
	"One the best things that they do is how they are able to, especially through this internship program, to get people involved" (FK01PI) "It’s a big community thing. A lot of people are involved or want to be involved" (KT08DI)					

	Divers	3	3	0	0	2	1
		"The best thing that organisation does, is involve volunteer divers" (FK23CP) "Reach out and involve the dive industry in the restoration program." (SC20DI)					
	Schools	3	3	0	2	0	1
		"There's also schools who come visit" (LG11PS) "[level of engagement]...especially younger people. Early-career individuals or those in the early stages of college" (SC01PS)					
	Locals	2	2	0	1	1	0
		"It gets the local community very involved" (FK26DI) "… also the locals that are involved in the making of the frames" (LG11PS)					
	Tourists	2	2	0	2	0	0
		"It's good to have guests involved" (LG05DI) "The involvement of the public, the guests... (LG09PS)					
Practical experience		11	11	4	4	3	0
		"People learn what they're doing and then go and apply it under the sea so I think they get a lot more out of it." (KT11PI) "It also encourages active participation of guests - so some sort of ecological reconstruction experience for the people." (LG26DI) "The understanding of what we're doing and then putting it under practice. I think it's fantastic. We learn, we put in into practice" (KT19PV)					
Beauty		9	12	2	6	0	1
		"The intrinsic, aesthetic beauty can never be estimated." (LG23TI) "To see the corals looking beautiful at some of the out-plant sites" (SC24PS)					
	Diverse	2	2	1	1	0	0

		"It's a favourite because there's so much biodiversity and you can see how much growth is happening already." (KT07PI) "it brings colours quickly and plus it attracts a lot of fish in the area where we keep the coral frame." (LG18DI)					
	Covered in corals	1	1	1	0	0	0
		"Now it's beautiful- and all our structures are covered in corals, you can't even see the metal. In between all the structures it's covered." (KT06PS)					
Provide hope		7	9	0	0	5	2
		"… and it is a hopeful thing when you grow the baby coral and you look and you see where it's planted growing up into a new reef. It is a warm and fuzzy in the darker tale of what's happening to coral reefs globally." (SC12PS) "It's providing a hopeful message about the future that while we are being destructive in certain ways, we also have it in our own hands to be able to fix things for the future." (FK03PI) "It gives everybody hope. It's something that is the good news." (FK07CP)					
Foster partnerships		5	6	0	0	4	1
		"It can be a great partnership, and a great learning exchange." (FK05CP) "I think their expansion to other parts of the world is good too." (FK19DI) "They're helping China setting up some of their reefs, and I think they're talking about expanding a lot. So, I like how widespread their effort is, it's not just the Caribbean" (SC14PI)					
Exemplary		4	5	0	2	0	2
		"I think this is something that we started doing and also the other resorts are doing it now from learning from us" (LG14DI) "The local visibility- I think that's great. Because a lot of people know TNC here in St Croix, for our coral restoration work. " (SC12PS)					
Legacy		1	1	0	0	1	0

			"I mean the way it is so future generations will get to see it at least a little bit." (FK09TI)					
	Legislative support		1	1	1	0	0	0
			"Recently we even had the mayor come down and say that it was wonderful after the last clean-up, that it brought the entire community together and he sees that importance now. So hopefully he'll implement some of these changes." (KT23DI)					
Ecological benefits			**80**	**133**	**21**	**25**	**16**	**18**
	Ecosystem function		54	67	13	20	10	11
			"… without you guys helping the restoration, the ecosystem here would fail and crumble." (FK09TI)					
		Diversity of marine life	28	28	6	15	6	1
			"It's going to attract more fish life, diversity, it's going to help in the health in general, and help the corals grow and diversify." (FK24DI) "… because it turned this area, which I couldn't imagine had much before, into a really really diverse spot around the island." (KT10PI) "We have more corals, it's a new home for the invertebrates and the small fish and everything to come" (LG01PS)					
		Habitat protection	20	20	5	3	2	10
			"Increasing the resilience of the reef." (KT28PS) "Put back strong, live coral into the system" (SC12PS) "You see those spats growing up into places that will eventually create this umbrella and can coordinate a real restoration process- and one that will reduce the man-made damages that are causing it to die." (SC28PV)					
		New habitat	15	16	6	9	0	0

		"Expanding the natural reefs we have here." (KT28PS) "The creation of habitat is an important one" (LG29PS) "Bringing back a reef to an area that was just sand" (LG11PS)					
Corals		37	44	9	7	13	8
	Species conservation	12	14	2	0	4	6
		"Bringing back *Acropora* to reefs that no longer have it. Especially to reefs where we know they were there a decade ago because we can still see remnant colonies, free-standing in some places." (FK12CP) "You can dive on any given site and never see a staghorn coral. So there really is a need to restore that- and also the Elkhorn." (SC20DI) "The coral nurseries are just phenomenal, and it could be like Noah's Ark." (KT25PV)					
	Growing well	12	12	5	2	3	2
		"It is good because the corals are nicely growing, it goes fast"(LG22TI) "Some places are really growing well" (KT02LO) "… to see staghorn grow up so quick" (FK19DI)					
	Increase coral cover	11	11	1	4	4	2
		"The fact that it kind of replenishes the reef. In some places there was nothing and now it's really built up. There's lots of corals there" (LG24PS) "It seems like they are- they've out-planted a lot. It seems like the out-plant are doing pretty well" (SC14PI) "We are restoring coral cover at the sites we are out-planting corals to." (FK05CP)					
	Coral diversity	4	4	1	1	2	0
		"One of the things we really promote is diversity in what we are restoring. So diversity of species, plus diversity within a single species." (FK14PS) "Trying to sustain the coral diversity and health generally is super important" (KT22PI) "I am going to say preserving genetic diversity" (FK28PS)					

		Look healthy	1	1	0	1	0	0
			"Some [corals] are really really healthy" (LG14DI)					
		Securely attached	1	1	0	1	0	0
			"I think epoxy like the block structure when we epoxy fragments in the cracks. I think these work well" (KT07PI)					
	Flow-on benefits		18	21	11	4	2	1
		Actions that further reduce damage	14	15	11	1	1	1
			"We have a reef resilience program where we are not just planting corals but looking at reducing threats to coral reefs at the same time." (SC18PS) "… just having that so people don't have to go collect from wild colonies is really, I think it's a good thing (FK05CP) "Fantastic way to attract divers to new sites and reduce stress on natural reefs- creating alternative dive sites for the divers is super important." (KT28PS)					
		Coastline protection	5	5	0	4	1	0
			"Without our coral reef systems. If they were to be destroyed, they act basically as big surge protectors. When big waves come in here. If our coral reefs are weakened and start to crumble and they start dying, we'll start flooding here." (FK09TI) "It will also help prevent erosion of the island." (LG20LO) "The islands are not very high so they need the corals to protect from the nature and the sea and stuff." (LG17PI)					
Project appreciation			**37**	**55**	**10**	**5**	**14**	**8**
	Scientifically -minded		22	24	6	3	9	4

	Scientific approach	13	13	4	1	5	3
		"I think they are doing a great job of moving forward with coral reef research." (FK29PI) "it's done by marine biologists, I believe what they are doing. They know where to collect the corals, they don't just go and break things off. They know not to collect corals that are already under stress." (LG10TI) "The supporting materials they provide so textbooks, referencing to papers they got. They know externally what people are doing in this field as well. They have a structured approach, but they show different sources, different opinions which bring it back into the whole scientific round." (KT11PI)					
	Research opportunities	7	7	2	2	3	0
		"We can give corals to other researchers to do research work that may inform restoration. So they may be looking at disease resistance, you know, all these different things." (FK05CP) "… have an entire nursery of corals and to be able to work with an experiment, and do different things with them is pretty cool, and pretty rare around the world." (FK18PS) "A tool for making some basis for experiments, and science we can develop" (LG29PS)					
	Monitoring	3	3	0	0	2	1
		"I really appreciate this kind of renewed approach with sound science and data collection" (FK02PS) "They are documenting it and sharing that knowledge with people around the world." (SC11CP)					
Doable		9	10	3	2	4	0
		"It's not too complex. It's a simple idea" (LG05DI) "It's really easy. You might have the opinion that it's complicated but it's actually quite simple. It's mostly underwater gardening." (KT09PS), "They are very easy to propagate, easy to grow from themselves." (FK11PS)					
Active work		8	8	3	0	4	1

	"I think the most important thing is that we go out consistently to do restoration work." (KT09PS) "We have a very active approach. So, one of the things that drew me to CRF was this idea of like actually working towards making a difference and being proactive about something." (FK14PS) "I'd probably say the amount of what we actually go out." (FK15PS)					
Well-organized	6	6	2	0	2	2
	"It seems like they have a pretty streamlined method. Like it seems that they have a pretty solid method for like the trees, and the nurseries. They've worked a lot in the past at making it as good as possible." (SC10PI) "They have a good system set up in the sense that they are organized, you know, it's been easy for us to learn because it's pretty simple how you go through about the day." (FK29PI) "I like the way the program is built- I think it's interesting to give us knowledge, information about all the marine ecology and everything that's happening and then apply it." (KT29PI)					
Well-supported	3	3	0	0	1	2
	"I think that's a really good thing. The other great thing is that they have a lot of supporters. They do a lot of outreach events, so they have you know fortunately a decent amount of financing to do the work they need to do. A third thing is that they have a very strong volunteer force with the internship program." (FK26DI) "They are able to fund their ideas, and that they do get volunteers to help them" (SC22DI) "They do get a lot of outside help (SC30FI)					
Diversity of project	2	2	1	0	0	1
	"I think the type of diversity of projects is the second best thing. We got things all the way from Biorock, to reef balls, flat table nurseries, art sculpture, buoyancy aids to shipwrecks. So there's a lot of different things." (KT09PS) "We're starting to crack into new, innovative ways with coral labs. So we're starting to do land-based nurseries. And I think that's the next step and it's totally exciting and totally new" (SC29PS)					

Positive experiences		**35**	**42**	**15**	**4**	**11**	**5**
	The people	18	18	7	8	0	3
		"I think the best thing is the people. I think that we are all pretty high intensity workers and everyone is very motivated and dedicated to their particular projects". (FK02PS) "The interaction between multiple people, different backgrounds, volunteers, interns and all that kind of stuff" (FK25PS) "They go out and they are very detailed. Maybe that's part of being proficient but they are dedicated and efficient, and you can tell they love what they do." (SC27DI)					
	Noticeable progress	15	15	8	3	2	2
		"If you look at some of the work that was done 2 years ago you can already see how the coral grow- so you see the efficiency of what you are doing. You see that it works. I like that." (KT29PI) "Some of the coral frames, I have seen them growing" (LG14DI) "It's more tangible. You know we're growing, we're planting- there's a full circle story. You can tell that you can actually see the impact." (SC12PS)					
	The fun	4	4	1	1	2	0
		"That it is very fun to learn different techniques about restoration." (KT30PI) "It's even fun for the guest" (LG13DI) "… get people to really enjoy it." (FK01PI)					
	Rewarding	3	3	2	0	1	0
		"I'm very proud of everything that they have undertaken." (FK11PS) "I think just really satisfying to see the corals and see that you're making a difference." (KT12PV) "The opportunity to be here and do such a nice work. You receive so much more than you give" (KT26PS)					
Economic benefits		**22**	**25**	**3**	**12**	**4**	**3**
	Increased tourism opportunities	14	15	1	7	4	2

		"It’s also bringing a lot of divers" (FK20DI) "For tourism. Underwater is the main thing so it’s better for tourism." (LG12TI) "For the local economy, to bring the tourists here" (LG23TI)					
	Increased accessibility to the reef	3	3	0	3	0	0
		"So here, they can just go straight from the beach. You can also see the marine life- straight from when they arrive on the jetty." (LG16TI) "From a property, marketing point of view, enabling the guests to see that from the shore." (LG02TI)					
Profit from project		6	6	0	5	0	1
		"The other advantage for us is the money that we get." (LG18DI) "I think it’s helping to raise funds" (SC16LO)					
Low cost		2	2	2	0	0	0
		"… fairly inexpensive and simple methods that can help." (KT24PI) "You don’t need a lot of money, you just need to scuba dive- you need needles and a structure, and you can do some restoration." (KT29PI)					
Food security		1	1	0	1	0	0
		"… which means they will have better food security." (LG20LO)					

Table S5.4 Summary table of the coding for limitations among responses to the question "What would you say are the three greatest problems about the coral restoration program" at all four case studies. Number of sources refer to number of respondents, while number of references refers to the responses that fit within each theme, sub-theme, and category. N=96 respondents

Emerging themes	Sub-themes	Categories	# sources	# references	KT sources	LG sources	FK sources	SC sources
Technical limitations			**56**	**84**	**18**	**10**	**16**	**12**
	Lack of capacity		26	34	6	2	7	9
			"We do not have the capacity, TNC did not have the capacity to intervene with any probation to the annual work." (SC01PS) "The lack of capacity. I think we could get a lot more done, but we just don't have the capacity here." (SC29PS)					
		Limited number of people involved	15	16	3	1	3	8
			"We don't have enough people to go out on the boats and stuff, we don't have enough people do all that we want to do of course" (FK18PS) "We could do with more people." (LG24PS) "You don't necessarily have the staff and the manpower to do it. So, it kind of seems like some of the things going forward might be hard to achieve." (SC10PI)					
		Lack of funding	14	14	3	1	4	6
			"They have a really limited budget. If they had way more money then, they could do a lot more, but you know" (FK13DI) "I'd say that we have a lack of funding. The work we're doing is under-appreciated and we could definitely benefit from finding funding in more available means. It's challenging that we struggle a bit financially and that gets in the way of the work eventually" (KT28PS) "The actual funds going to the program to do the work is limited, and in my opinion below a level, the funding is less than a level necessary to do the work properly." (SC01PS)					

Project design		11	13	2	6	3	0
	Material used	5	6	2	2	1	0
		"Definitely the plastic, I'd like to go back to that. Because I'm proud that we are moving away from it but we're still very very very reliant on it." (FK11PS) "Concrete is heavy and hard to carry to the ocean. And also, it contributes to climate change with CO2 release. I think one the challenges with restoration at the moment is finding a material that is as strong as concrete but doesn't have the same environmental problems." (KT06PS) "The way in which we build the frames. It's metal and we put sand and resin fibre. We attach the corals with cable ties. And after a few months, it starts to rust between the resin and the metal."(LG22TI)					
	Location of transplantation	3	3	0	2	1	0
		"Here, the topography of the reef is not easy so some of the frames are not very stable so some frames that we put on rubble 10 years ago are now buried in the sand." (LG09PS) "Some of the frames are a bit too quick to move to the deeper part." (LG14DI) "Where the corals are actually being planted. I think they could do a better job with that." (FK15PS)					
	Not enough diversity of projects	2	2	0	2	0	0
		"If we could make bigger, funnier shapes would be more fun. Also, I saw reef balls which are another type or just fragments in the cement. I didn't make much research about it. But yes, it would be cool to have bigger shapes. Just in case they die, we have a big structure to work with." (LG03DI) "Since the coral frames themselves, that's kind of a set program it could be good to have other coral projects to expand I don't know." (LG05DI)					
	Timing of transplantation	1	1	0	0	1	0

		"They were doing a fair bit of out-planting during the summer, during stressful times. And I know they were out-planting to some reefs here in the middle Keys, near shore, in the summer, right before bleaching season." (FK16CP)					
	Type of coral used	1	1	0	0	1	0
		"I really hate that we're working with that [fire coral] because it's just a waste of resources, a waste of the plastics, a waste of space. I'm a little bitter about it. It burns. Laugh. It's a painful coral." (FK11PS)					
Not enough scientific background/ focus		10	12	4	2	2	2
		"We need more research. There is plenty of things to research on diversity, bleaching, disease, reproduction. Looking at whether our fragments are reproductively viable is key." (LG09PS) "It would be nice if there was a little more science embedded in the methodology." (SC14PI) "Real scientists need to be involved in this organisation to figure out what will make it work and not work" (FK23CP)					
Amateurism From volunteer workforce		9	9	5	0	4	0
		"Sometimes you do more wrong than good if you're not experienced enough. It's good to let us go ahead as soon as we arrive but at the same time I think it might be an issue" (KT29PI) "The way that they portray it "*even if they screw it up and don't really do things well, it doesn't matter, they are getting experience*"- I really don't agree with that." (FK01PI) "You go with new student you see them struggling and that result in them doing a bit of a lousy job. The fragments might not be well secured and might fall off in the future." (KT07PI)					
Requires a lot of work		4	5	0	4	0	0

		"It is very time consuming- monitoring all the frames. Sometimes in certain places they will die and re-transplanting them takes a lot of time" (LG24PS) "Problem is the project is getting really big. Now we have 2900+ frames- I don't think there's any project bigger than that in the world [...] and that's a lot of manpower- it's like you have a huge garden and you have to take care of it." (LG25PS)					
	Expensive	4	4	2	0	1	1
		"Sometimes new divers, student divers, don't have the funds to do a conservation dive." (FK17TI) "It costs a lot of money for interns and students" (KT01PI)					
	Outcome uncertainty	3	3	1	0	2	0
		"We don't know if it's going to work." (FK10CP) "There's uncertainties regarding the long- term efficacy of our efforts. And it's a bit terrifying." (KT28PS)					
	Diving security	2	2	2	0	0	0
		"I know it's a research place and there's a lot of single diving, but they have to understand that not everyone has a background of diving and the security has to improve." (KT19PV)					
	Limited site accessibility	1	1	1	0	0	0
		"It would be nice to have it in other places as well- not just the remote areas. It would be nice to have it in dive sites that are used more often." (KT23DI)					
Management limitations		**41**	**88**	**12**	**6**	**10**	**13**
	Disconnect with local community	18	29	5	1	5	7

		"The people who restore or help and people who benefit from it are not involved." (KT02LO) "The locals are not interested in helping out on conservation projects. As far as I've seen. I know a lot of that stuff is people who move here and are interested in these kind of conservation efforts."(SC25DI)					
	Lack of communication with the public	14	18	3	1	5	5
		"It doesn't seem like that there is a lot of outreach to others- maybe advertisement, or maybe letting the dive community know. "*Hey, that's what's going on*", or "*That's what we're offering*"."(SC27DI) "I think generally advertising themselves better. It's not known what they do" (KT11PI) "I think communication with the general public is probably a little bit lacking." (FK03PI)					
	Lack of community awareness	7	8	2	0	3	2
		"I think there isn't enough awareness about the organisation as a whole." (FK01PI) "So, there is very limited awareness of what they are doing, how they are doing it, everything- limited awareness." (SC05DI) "I don't know that we are spread through the community very effectively." (SC18PS)					
Lack of partnerships		13	14	5	0	4	4
	With local dive shops	10	10	5	0	2	3
		"… with all the dive school around the island… I know they tried to bring them together, but it didn't work. As long as there's only one dive school doing restoration, nothing major is going to change" (KT29PI) "There is a complete lack of engagement with the dive shops, and specifically the instructors and dive guides." (SC05DI) "There are other [dive] schools that do conservation as well, but they do separate things." (KT02LO)					

	With other restoration practitioners/ conservation groups	2	2	0	0	1	1
		"The term partnership is too loose and there should be more of a coordinated effort if it's going to be a population enhancement project." (FK12CP) "We're always doing the reaching out and it's tiring and frankly I think inappropriate." (SC04CP)					
	Internationally	1	1	0	0	1	0
		"CRF should be this local community that is branching out internationally in the sense that it ships trees to people and give them a sort of start-up package." (FK29PI)					
Lack of monitoring		9	10	1	1	5	2
		"Long term and large-scale monitoring is probably our biggest issue. Because, it's just hard to understand the success." (FK05CP) "It's not being followed enough. It's being monitored but not in a very efficient way." (LG28PI) "I think the long-term monitoring and seeing what the efforts are worth after a couple years is the largest concern for me." (FK26DI)					
Inadequate time management		9	9	3	1	3	2
		"Sometimes as an intern we tend to sit around and do nothing in the morning" (KT24PI) "Time is used to do things that are not always necessary so yeah I think staff time could be used in a more efficient way." (LG28PI) "I think the possibility of using volunteers in a better way is probably in their capacity." (SC28PV)					
Lack of education		5	9	1	0	1	2

		"I would like to spend more of this money towards the education part of the program." (FK23CP)					
	For the locals	2	2	1	0	0	1
		"It's not enough education for the people who are out there. The fishermen, the locals" (KT20DI) "It would be nice if the locals, especially the children appreciated the corals more, so if they understood why the group is doing what they are doing, and why it would benefit them. So, it would be nice if there was a little bit more noticeable local education" (SC19DI)					
	For the diving community	2	2	1	0	0	1
		"Educating the dive community and being like "guys, this is really an issue"." (SC27DI) "The divers. There's not enough education and respect shown by those guys for the reefs." (KT20DI)					
Commerciality of the operation		5	5	1	4	0	0
		"They still think too much about business" (KT02LO) "It's a commercial thing here- so it's based on money." (LG13DI) "Other thing would have to be the guest constraint. Sometimes if a frame dies, we have to replace some fragments to please the guests. It's not about whether putting a fragment back is a good idea" (LG28PI)					
Quantity over quality		4	5	0	2	2	0
		"They should spend less energy towards "*we've planted a million corals this year!*". It's ok to plant less corals and affect more people, or publish more papers, in my opinion." (FK23CP) "I think any projects like anything, if it's in danger of getting too big and not properly managed, then it can be to its own detriment" (LG02TI) "They are doing more mass quantity versus quality." (FK29PI)					

	Lack of leadership	2	2	1	0	1	0
		"There needs to be some sort of leadership to make that work." (KT23DI)					
	Inadequate infrastructure	2	3	0	0	2	0
		"I think having the like technical infrastructure, techie bits of it. We use excel at the moment, and that is limited in what we can do in the capacity." (FK02PS) "Where we are located. This not an ideal space for us- the building is kind of tucked behind off of the highway, so we don't get a ton of visitor traffic." (FK02PS)					
	Over-ambitious	1	1	1	0	0	0
		"Sometimes we get projects that are a bit big for us, so we get stressed." (KT26PS)					
Ecological limitations		**33**	**42**	**5**	**15**	**8**	**5**
	Lack of coral diversity	10	11	0	5	1	4
		"I think the cloning. The fact that we have a couple of copies of the same genetics-" (LG08PS) "… because you're only using certain coral species. Because these species are hardy and survive better- so it's only certain kind. And if now we say that we're only going to use certain ones that are resistant to bleaching then that's reducing even more" (LG23TI) "We've only been focusing on Elkhorn and Staghorn corals whereas a healthy reef has a lot more diversity than that." (SC18PS)					
	Limited long-term survival	7	8	0	3	4	0

	"You watch them grow for maybe a year or two and then they are dead. And, I have seen that happening for years and years." (FK23CP) "A lot of fragments do die." (LG11PS) "I see a lot of their staghorn corals that they plant. A lot of it is dead. I see the tag and I see them grey stones." (FK24DI)					
Negative impacts from diving and snorkelling	7	7	4	1	1	1
	"We welcome student that can be beginners meaning they can kick the restored corals with their fin and damage things which is the opposite of what we are trying to do." (KT30PI) "Lots of people do not have the awareness of snorkelling without kicking the corals, damaging- it's heart breaking to see that happen when they've spent months and years trying to build this reef up." (LG02TI) "A lot of the areas are well dived and that can actually affect the coral." (SC30FI)					
Damage to natural reefs	7	7	0	7	0	0
	"If they don't have the proper knowledge, it could actually damage the parent colonies from where they are getting the pieces of corals" (LG20LO) "Another thing that bothers me is that we always take wild colonies rather than taking corals from the frames or some that fell down" (LG24PS) "I think it's negatively impacting the biodiversity of the reef itself. Whether or not we should be messing out with natural selection. If you're going to do it, at least try to maximise the number of species." (LG23TI)					
Artificial	5	5	0	3	2	0
	"You have to hammer things into the rocks so you're putting something man-made in the environment." (FK20DI) "It's not very attractive, it would be great if they could be more naturalistic. If the frames are completely covered- great, but it's difficult. " (LG23TI) "It feels very handmade, it's not very natural." (LG21TI)					

	Corals don't grow well	3	3	1	2	0	0
		"I mean sometimes you see some frames that don't grow that well" (LG07DI)					
Restoration limitations		**19**	**26**	**8**	**3**	**5**	**3**
	Scale of threats outweighs solutions	14	15	7	3	3	1
		"When you hear about what's going on around the island like that time when they built reservoirs and washed down lots of sediments in the bay. So yeah, you're doing a lot of efforts but with all the activity around the island, at some point it's limited." (KT29PI) "I mean coral bleaching is not helping the restorations. It makes the restoration a futility." (LG26DI) "I know we wish we could do more things that affect the restoration. Like we're not able to work on stopping run-offs or how the roads are done, or when there's quarries that are running off into the sea, or even stopping fishing in certain areas. Stopping overfishing or stopping anchoring in certain areas" (SC24PS)					
	Limited spatial scale	5	5	3	0	0	2
		"Obviously a very localised effort. That it's you know you're just repairing a part of a reef and that isn't a larger scale thing" (SC12PS) "It's small scale- we help a few reefs on Koh Tao and it's not enough at all" (KT01PI) "We have wanted to take things to scale and actually plant corals on the entire reef sort of scale. But we haven't really been able to that" (SC18PS)					
	Not addressing the cause of decline	4	5	2	0	2	0

		"It's like using duct tape over something that's broken. It doesn't fix the problem; it just helps you get to your next destination kind of thing." (FK14PS) "The problem is global and this is just one local solution. We put corals back on the reef, but it doesn't stop bleaching or tourism and people who would go break it. Even the pollution on Koh Tao. We're just helping the surface problems." (KT01PI) "We're not addressing the original causes of degradation." (FK28PS)					
Staff limitations		**11**	**14**	**0**	**2**	**8**	**1**
	Ego	6	7	0	0	5	1
		"There is too much turf battles and pride and less teamwork than there needs to be." (FK28PS) "I think they have too tight of a reign on it. I think in their opinion, they are the only ones that can do this, and if you're not a part of their group, you're not welcome." (SC20DI) "People can be defensive, and want their idea to the best, and they're not opened. It's frustrating" (FK15PS)					
	Lack of communication among staff	4	4	0	0	4	0
		"Things feel a little disjointed. The information one person gets doesn't fan out to all the other people that need it. And you're always hunting people down to ask some questions." (FK11PS) "So even though it's very small and you think everybody is talking back and forth, that's not always the case. And like sometimes it can really hinder things if you're waiting for somebody to do something, but they don't know that they're supposed to do something. " (FK14PS)					
	Lack of long-term commitment	2	2	0	2	0	0

		"I'm actually very disappointed by the way people look at this, that are sometimes involved in this, about how when I employ people- I feel this is an opportunity that is not valued. " (LG29PS) "People have to be very dedicated to it, and if we don't have that it's complicated" (LG25PS)					
Legislative limitations		**5**	**6**	**2**	**0**	**3**	**0**
	Constraints due to permitting	3	3	0	0	3	0
		"A lot of the issues are basically constraints due to permitting" (FK12CP) "Permitting requirements which are very specific, and tedious, and time consuming. So, one of the flaws is that we are held back in our ability to do things based on what we are permitted to do, permitted to report." (FK14PS)					
	Lack of government funding	1	1	1	0	0	0
		"They give budget without thinking about what's actually needed." (KT02LO)					
	Lack of regulations and enforcement	1	1	1	0	0	0
		"We're working on trying to get things enforced, but it's difficult, it's not easy. We have to go through the government here which is already difficult" (KT09PS)					

APPENDIX S6

Summary tables for responses to the question on the importance of coral restoration programs across the four dimensions of sustainability

Table S6.1 Summary table of the coding for responses to the question “How important do you think the restoration efforts are for Location X in terms of a. ecological, b. socio-cultural, c. economic, d. governance from 1 to 10 where 1 is “not at all important” and 10 is “very important”? at all four case studies. Number of sources refer to number of respondents. N=120 respondents

Question	Positives/negatives	Sub-themes	# sources	KT sources	LG sources	FK sources	SC sources
Ecological importance	**Positive**		**36**	**7**	**9**	**11**	**9**
		For the reef	16	5	5	4	2
		" Without the corals, then the fish don’t come. And you know it’s the whole." (FK06DI) "1000s of divers that come and obviously put a lot of stress on the reefs. So I think if that work wasn’t being done then the reef wouldn’t last very long" (KT24PI)					
		For the action	8	1	1	3	3
		You’ve got to try, you’ve got to do something. (FK16CP) "It’s always good that we’re trying something." (LG26DI)					
		For the corals	7	2	1	4	0
		"We’re preserving genetic diversity. We’ve got strains that don’t exist on the reefs anymore. So if nothing happens maybe they’d disappear." (FK28PS) "These corals are not coming back on their own so the effect of planting is huge (FK11PS)					
		For the fish	3	0	0	0	3
		"If we lose the corals, we’re going to lose a whole lot of different species of fish" (SC25DI) "[The restorations is a] big thing for the fish and that’s where the fish live" (SC09DI)					
		For science	1	0	0	1	0

		"CRF recently has been adjusting their program to do more research. So if they can do that and provide more information around then I think it's great" (FK26DI)					
	Negative		**8**	**1**	3	**4**	**0**
		Inadequate scale	4	1	1	2	0
		"The destruction goes a lot faster than the restoration. If we have some environmental issue like coral bleaching they'll die anyway. It's a small scale effort" (KT01PI) "if you do it with just 1 type of coral, it's not the best idea" (LG18DI)					
		Outcome uncertainty	4	0	2	2	0
		"Since we have this El Nino thing- it's not quite clear if these corals will survive or not." (LG26DI) "What happens to these corals a couple years after that is equally as important. You can plant every day, all day but if they continue to die, we're not doing much" (FK26DI)					
Socio-cultural importance	**Positive**		**38**	**11**	**9**	**9**	**9**
		Education	20	9	6	3	2
		"When they go on dives they'll be more conscious about not touching the reef and I think that education is probably more valuable than the work they'll do during that week" (KT24PI) "The idea is not just to restore the environment but also teach people how to conserve it and how to take care of the environment." (LG07DI)					
		Awareness	16	3	3	6	4
		"It is important to branch out and make sure everyone is aware of what they are doing and the socio-economic impact that they can have because that will draw more people to support them." (FK29PI) "Can spread the awareness that corals are dying and that you can help out through very small things" (SC09DI)					
		Stewardship	5	2	1	1	1

		"Students say what they enjoy most is to be hands on with the corals and the structure and being able to see what difference it's making. It gives them a sense of ownership and I think that fosters a sense of responsibility" (KT15PS) "It gives people a reason to care and it gives people a way of doing something" (FK26DI)					
	Negative		**12**	**2**	**1**	**5**	**4**
		Limited outreach	10	2	0	4	4
		"I haven't seen many locals involved." (KT25PV) "They could do more in involving the dive instructors who dive everyday, who live here." (FK24DI)					
		Limited education	1	0	1	0	0
		"I think the guest come here to buy the frames for a memory- even they take pictures. It's just memory. I don't think they know much about how it's important." (LG06DI)					
		Potential negative drawbacks	1	0	0	1	0
		"There's actually some people out there who use it as fuel against restoration. They'll say that if too many people feel like "All we have to do is plant new corals and it will fix all the problems", they will stop being concerned about burning too much fuel or you know, wearing the wrong sunscreen which can have impacts, or other things" (FK12CP)					
Economic importance	**Positive**		**41**	**12**	**8**	**9**	**12**
		For the tourism industry	28	7	5	9	7
		"It is important for all the fisheries and the dive because diving here is huge, it's what people come in the Keys to do. There is no beach so you have to go diving." (FK01PI) "Everyone on the island is diving. I mean there are other people, but the majority is relying on the reef and people are not going to continue coming here if the reef keeps on deteriorating." (KT07PI)					

		For people involved	5	2	2	0	1
		"So economically it’s a new niche. You go tech diving, you go wreck diving- there’s no reason why conservation diving wouldn’t take off." (KT11PI) "It can be an important source of employment. I just proved it by providing employment on an island of 15 people with no real employment perspective" (LG29PS)					
		For local economy	5	0	1	2	2
		"But also the marine life will be better, giving for example more fish for fishermen. So in that point of view yes, it’s beneficial for lots of people. (LG07DI) "It’s 6 or 7 years into the work and we spent well over a million dollars in a small economy so yes. A lot of gas and tanks." (SC01PS)					
		For ecosystem services	2	1	1	0	0
		"What reef provide for people in terms of ecosystem services like food, protection for erosion and so on. If our efforts can slow down the loss of these services, then it’s very important." (KT28PS) "Economically, if we’re looking at building walls around 195 islands where people are living, it is very expensive. So this restoration work will definitely help reduce that cost. And also, with these walls there are costs associated with maintenance. But if you have a healthy reef around the island then the reef on its own is maintaining it and protecting the people and the communities." (LG20LO)					
	Negative		**15**	**4**	**2**	**3**	**6**
		Limited scale	9	2	2	1	4
		"Economically, it’s not going to protect the shore yet because it’s not going to be strong enough." (SC24PS) "There’s a lot of things happening around the world that have more effects on the economy. I noticed that we used to have a lot more whalesharks and sharks and they used to bring a lot more people" (KT23DI)					
		Expensive	1	1	0	0	0

		"Not so much because it costs money" (KT07DI)					
Governance importance	**Positive**		**42**	**8**	**9**	**14**	**11**
		To get institutional support	22	1	3	11	7
		"Critical for making the permitting easier, making the funding easier, and yeah, no absolutely, and it's also going to bring larger awareness to a larger audience if it can reach that sort of level as well." (KT12CP) "It's very important in terms of pointing out to the government that there is an issue" (LG11PS)					
		For institutional support	20	7	6	6	1
		"It is supported by the government, the government is helping some communities come up with projects and help them with ideas to come up with projects, apply for NGO funding and through that start these activities. " (LG20LO) "We just got that enormous NOAA grant. And we're basing our efforts on an Acropora recovery plan which nobody has ever done before. And both of those come from government agencies " (FK11PS)					
	Negative		**24**	**5**	**9**	**1**	**9**
		Support is insufficient	10	4	4	0	2
		"The government keep changing and they change project. There is no real support for conservation." (LG01PS) "I don't think it's from a lack of government wanting to try. But I don't think they have the time and resources and intonations to regulate it." (KT20DI)					
		Support is inadequate	7	1	2	0	4

	"Across the board, environmental licensee and everything- we really always fall down when it comes to enforcement." (SC11CP) "The government is very disconnected form almost anything that anyone does. I don’t even think there’s like a permitting process." (LG11PS)